4

GROUND WATER AND WELLS

4.1. GROUND WATER RESOURCES

The amount of water stored in the earth's crust may be of the order of 8 billion cubic kilometres, half of which is at depths less than 800 m (1). This water inside the earth is about 35 times the combined storage of all the world's rivers, fresh water lakes, reservoirs, and inland seas, and is about one-third the volume of water stored in the arctic and antarctic ice fields, the glaciers of Greenland, and the great mountain systems of the world (2). All of this ground water, however, cannot be utilised because of physiographic limitations.

The estimate of the present ground water resource in India (3) is of the order of 650 cubic kilometres (as against 1880 cubic km for surface water resources), out of which utilisable ground water is assessed at around 420 cubic km (as against 690 cubic km for surface water resources); see Table 1.4. *Ground water* is that part of the subsurface water which occurs within the saturated zone of the earth's crust where all pores are filled with water (2). Ground water has also been referred to as that part of the subsurface water which can be lifted or which flows naturally to the earth's surface. A hole or shaft, usually vertical, is excavated in the earth to lift ground water to the earth's surface and is termed a well. A well can also be used for disposal of water, artificial recharge, draining out agricultural lands, and relieving pressures under hydraulic structures. The Chinese are known to be the first to have drilled deep wells using bamboo rods tipped with iron (2). The rods were lifted and dropped manually and the method was similar to the method now known as cable tool drilling. Ground water flows to the earth's surface through naturally discharging springs and streams and rivers which are sustained by ground water itself when overland runoff is not present. Following significant features of ground water should always be kept in mind while managing ground water (2):

(*i*) Ground water is a huge water resource, but is exhaustible and is unevenly available.

(*ii*) Ground water and surface water resources are interrelated and, hence, should be considered together.

(*iii*) Excessive and continued exploitation of ground water must be avoided as natural replenishment of the ground water resource is a very slow process.

(*iv*) Ground water is generally better than surface water in respect of biological characteristics. On the other hand, surface water is generally better than ground water in terms of chemical characteristics.

(*v*) Ground water may be developed in stages on "pay-as-you-go" or "pay-as-you-grow" basis. Surface water development usually needs large initial capital investment.

(*vi*) Underground reservoirs storing ground water are more advantageous than surface reservoirs.

(*a*) There is no construction cost involved in underground reservoirs. But, well construction, pumps and energy for pumping water, and maintenance of pumps and wells require money.

(*b*) Underground reservoirs do not silt up, but surface siltation of recharge areas may appreciably reduce recharge rates.

(*c*) The evaporation from underground reservoirs is much less.

(*d*) Underground reservoirs do not occupy the land surface which may be useful for some other purposes.

(*vii*) Ground water is generally of uniform temperature and mineral quality and is free of suspended impurities.

(*viii*) Ground water source has indefinite life, if properly managed.

Ground water source is replenished through the processes of infiltration and percolation. *Infiltration* is the process by which the precipitation and surface water move downward into the soil. *Percolation* is the vertical and lateral movement through the various openings in the geological formations. Natural sources of replenishment include rainwater, melting snow or ice and water in stream channels, and lakes or other natural bodies of water. Rainwater may infiltrate into the ground directly or while flowing over the land enroute to a river, or stream, or other water bodies. Artificial sources of replenishment (or recharge) include the following (2):

(*i*) Leakage from reservoirs, conduits, septic tanks, and similar water related structures.

(*ii*) Irrigation, or other water applications including deliberate flooding of a naturally porous area.

(*iii*) Effluents discharged to evaporation or percolation ponds.

(*iv*) Injection through wells or other similar structures.

4.2. WELL IRRIGATION

In view of the large amount of utilisable ground water, higher agricultural yield of tubewell-irrigated lands in comparison to that of canal-irrigated lands (see Table 1.3), and favourable impact of its use on waterlogging, it is only logical to develop ground water resources for irrigation and other activities. Most of the existing canal systems in India are of a protective nature, *i.e.*, they provide protection against famine. They were not designed to promote intensive farming. Well irrigation ensures more reliable irrigation and, therefore, enables the farmers to grow more remunerative crops with improved yield. The following are the main requirements for the success of well irrigation:

(*i*) Presence of a suitable aquifer which can yield good quality water in sufficient quantity.

(*ii*) Availability of energy, preferably electric power, for pumps.

(*iii*) Well distributed demand for irrigation throughout the year.

(*iv*) Suitable configuration of command area with the highest ground around the centre of the command area.

In general, well irrigation is more efficient than canal irrigation. The following are the comparative features of the two types of irrigation:

(*i*) In the canal irrigation system, major structures, such as headworks, main and branch canals, etc. must be constructed prior to the start of proportionate agricultural activity which grows gradually because of the availability of irrigation facility. But, wells can be constructed gradually to keep pace with the development of the agricultural activities of the area.

(*ii*) Transit losses in well irrigation are much less than those in canal irrigation system.

(*iii*) Isolated patches of high lands can be better served by well irrigation.

(*iv*) Well irrigation offers an effective anti-waterlogging measure of the affected lands and reduces the chances of waterlogging of canal-irrigated lands.

(*v*) Well irrigation ensures relatively more reliable supply of water at the time of need. This results in better yield. Besides, farmers can switch over to more remunerative crops due to the availability of assured supply.

(*vi*) Well irrigation needs energy for pumping. Installation and maintenance of pumps and the cost of running the pumps make well irrigation costlier.

(*vii*) Failure of power supply at the time of keenest demand may adversely affect the yield in case of well irrigation systems.

It is thus obvious that both irrigation systems have advantages as well as disadvantages. Therefore, both must be used in a judicious manner to obtain maximum benefits, such that there is no waterlogging and the ground water resource can be maintained indefinitely.

4.3. OCCURRENCE OF GROUND WATER

The subsurface medium within which ground water occurs is either porous or fractured or both. The subsurface occurrence of ground water can be divided into two zones (Fig. 4.1): (*i*) the vadose zone or unsaturated zone or zone of aeration, and (*ii*) the phreatic zone or saturated zone or zone of saturation. In the saturated zone, all pores or voids are filled with water whereas in the unsaturated zone, pores contain gases (mainly air and water vapours) in addition to water.

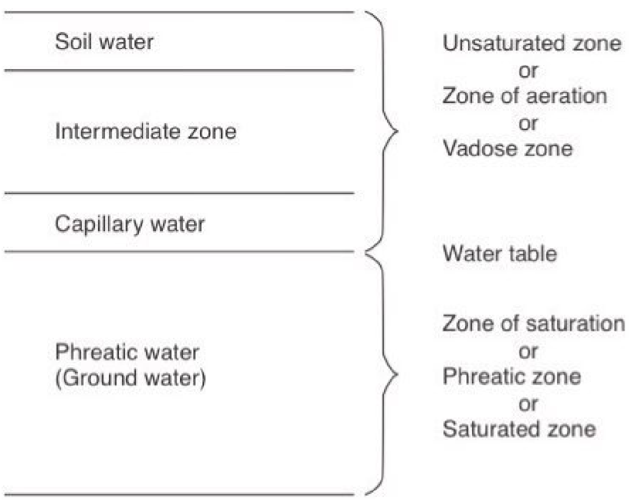

Fig. 4.1 Vertical distribution of subsurface water

The water table is defined as the upper limit of the saturated zone. However, it should be noted that all the pores near the base of the capillary water zone (which itself may range from practically nothing in coarse material to about 2.5 m or more in clay materials) may be completely saturated. The number of pores filled with water decreases in the upward direction of the capillary water zone. One can, therefore, expect the upper limit of actual saturation to be an irregular surface. *Water table* should, therefore, be redefined as the upper limit of saturation at atmospheric pressure.

The saturated zone containing interconnected pores may exceed depths penetrated by oil wells (more than 12,000 m). However, freshwater (part of the hydrologic cycle) is found only up to depths of about 800 m (2).

A saturated geologic formation capable of yielding water economically in sufficient quantity is known as an *aquifer* (or water-bearing formation or ground water reservoir). Ground water constantly moves through an aquifer under local hydraulic gradients. Thus, aquifers perform storage as well as conduit functions. Ground water may exist in aquifers in two different manners: (*i*) unconfined, and (*ii*) confined. The unconfined condition occurs when the water table is under atmospheric pressure and is free to rise or fall with changes in the volume of the stored water. An aquifer with unconfined conditions is referred to as an unconfined or water table aquifer. An aquifer which is separated from the unsaturated zone by an impermeable or very less permeable formation is known as confined aquifer (or artesian aquifer or pressure aquifer). Ground water in a confined aquifer is under pressure which is greater than the atmospheric pressure. The water level in a well penetrating a confined aquifer indicates the piezometric pressure at that point and will be above the bottom of the upper confining formation. Such wells are known as artesian wells and if the water level rises above the land surface, a *flowing well* results (Fig. 4.2).

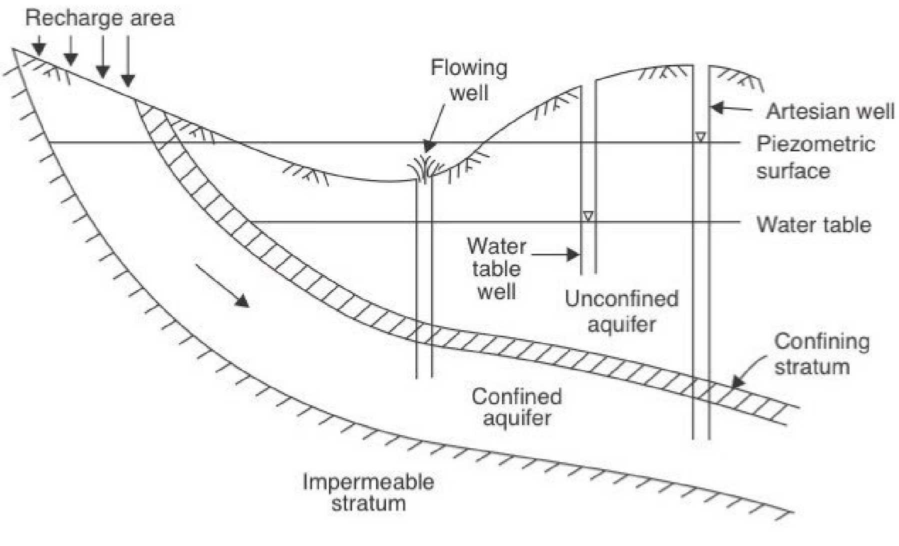

Fig. 4.2 Aquifers and wells

Water released from an unconfined aquifer is the result of dewatering or draining of the aquifer material. In the case of confined aquifer, the release of water is the result of a slight expansion of water and a very small compression of the porous medium (2).

The availability, movement, and quality of ground water depend mainly on the characteristics of the medium. The following characteristics of the medium affect the availability and movement of ground water.

Porosity can be defined as the ratio of the volume of pores to the total volume of the porous medium. It ranges from 0 to 50 per cent for most of the rock materials. For aquifer considerations, porosities less than 5% are considered small, those between 5% and 20% are considered medium and those greater than 20% are considered large (2). Porosity is, obviously, an inherent characteristic of the material independent of the presence or absence of water. For ground water studies, the interconnected pore space which can be drained by gravity should be used for determining the porosity and such porosity is known as effective porosity.

The *specific yield* of a soil formation is defined as the ratio of the volume of water which the soil formation, after being saturated, will yield by gravity to the volume of the soil formation.

The *specific retention* of a soil formation is defined as the ratio of the volume of water which the soil formation, after being saturated, will retain against the pull of gravity to the volume of the soil formation.

These definitions of specific yield and specific retention implicitly assume complete drainage. Obviously, the sum of the specific yield and the specific retention would be equal to the porosity of the given soil formation. The product of the average specific yield of a saturated water-bearing formation and its total volume gives the volume of water which can be recovered from the formation by gravity drainage. It may be noted that the time factor is not included in the definition of specific yield. However, the gravity draining of a formation decreases with time and may continue for years. Fine-grained materials may have lesser specific yield than coarse materials even though their porosity may be greater (Fig. 4.3 and Table 4.1).

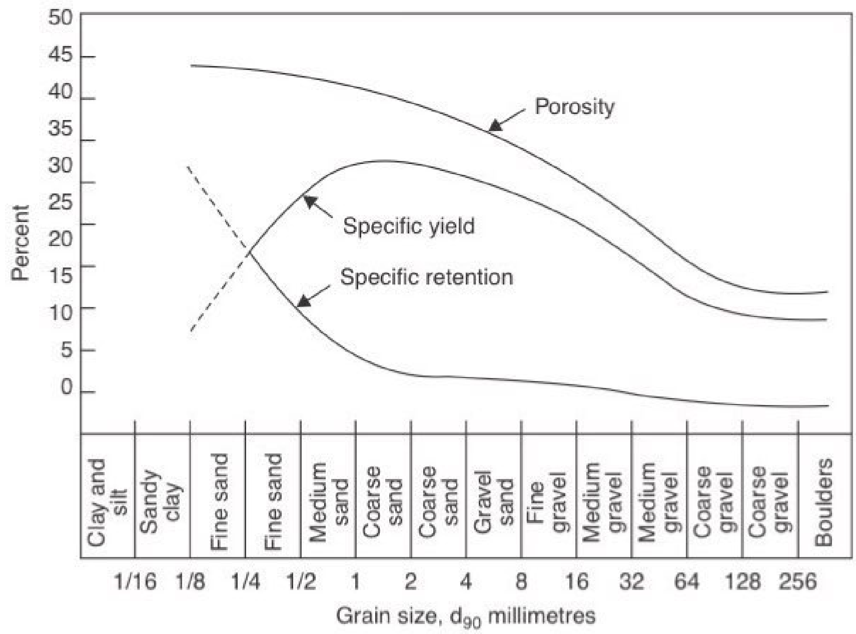

Fig. 4.3 Typical variation of porosity, specific yield, and specific retention with grain size (4)

Table 4.1 Representative porosity and specific yield of selected earth material

Material	*Porosity %*	*Specific yield %*
Clay	45 – 55	1 – 10
Sand	25 – 40	10 – 30
Gravel	25 – 40	15 – 30
Sand and gravel	10 – 35	15 – 25
Sandstone	5 – 30	5 – 15
Shale	0 – 10	0.5 – 5
Limestone	1 – 20	0.5 – 5

In case of confined aquifers there is no dewatering or draining of the material unless the hydraulic head drops below the top of the aquifer. Therefore, the concept of specific yield does not apply to confined aquifers and an alternative term, storage coefficient or storativity is used for confined aquifers. *Storativity* or *storage coefficient* is defined as the volume of water an aquifer would release from or take into storage per unit surface area of the aquifer for a unit change in head. Its value is of the order 5×10^{-2} to 1×10^{-5} (2). For the same drop in head, the yield from an unconfined aquifer is much greater than that from a confined aquifer.

The *permeability* of a porous medium describes the ease with which a fluid will pass through it. Therefore, it depends on the characteristics of the medium as well as the flowing fluid. It would be logical to use another term which reflects only the medium characteristics. This term is named intrinsic permeability, and is independent of the properties of the flowing fluid and depends only on the characteristics of the medium. It is proportional to the square of the representative grain diameter of the medium, and the constant of proportionality depends on porosity, packing, size distribution, and shape of grains.

The permeability of a medium is measured in terms of hydraulic conductivity (also known as the coefficient of permeability) which is equal to the volume of water which flows in unit time through a unit cross-sectional area of the medium under a unit hydraulic gradient at the prevailing temperature. The hydraulic conductivity, therefore, has the dimensions of $[L/T]$ and is usually expressed as metres per day or metres per hour. It should be noted that an unsaturated medium would have lower hydraulic conductivity because of the resistance to a flow of water offered by the air present in the void spaces.

The *transmissivity*, a term generally used for confined aquifers, is obtained by multiplying the hydraulic conductivity of an aquifer with the thickness of the saturated portion of the aquifer. It represents the amount of water which would flow through a unit width of the saturated portion of the aquifer under a unit hydraulic gradient and at the prevailing temperature.

Example 4.1 A ground water basin consists of 20 km^2 of plains. The maximum fluctuation of ground water table is 3 m. Assuming a specific yield of 15 per cent, determine the available ground water storage.

Solution: Ground water storage = area of basin × depth of fluctuation × specific yield

$$= 20 \times 10^6 \times 3 \times 0.15 = 9 \times 10^6 \text{ m}^3$$

Example 4.2 In an aquifer whose area is 100 ha, the water table has dropped by 3.0 m. Assuming porosity and specific retention of the aquifer material to be 30 per cent and 10 per cent, respectively, determine the specific yield of the aquifer and the change in ground water storage.

Solution: Porosity = specific yield + specific retention

$\therefore$ Specific yield = porosity – specific retention = 30 – 10 = 20%.

Reduction in ground water storage = $100 \times 10^4 \times 3.0 \times 0.2$

$= 60 \times 10^4 \text{ m}^3$.

4.4. FLOW OF WATER THROUGH POROUS MEDIA

Ground water flows whenever there exists a difference in head between two points. This flow can either be laminar or turbulent. Most often, ground water flows with such a small velocity that the resulting flow is laminar. Turbulent flow occurs when large volumes of water converge through constricted openings as in the vicinity of wells.

Based on a series of experiments conducted in the vertical pipe filled with sand, Henry Darcy, a French engineer, in 1856 concluded that the rate of flow, Q through a column of saturated sand is proportional to the difference in hydraulic head, Δh, between the ends of the column and to the area of flow cross-section A, and inversely proportional to the length of the column, L. Thus,

$$Q = KA \frac{\Delta h}{L} \tag{4.1}$$

Here, K is the constant of proportionality and is equal to the hydraulic conductivity of the medium. Equation (4.1) is known as Darcy's law and can also be written as

$$V = K \frac{\Delta h}{L} \tag{4.2}$$

in which, V is the specific discharge (or the apparent velocity of flow) and $\frac{\Delta h}{L}$ is the hydraulic gradient. Expressed in general terms, Darcy's law, Eq. (4.2), becomes

$$V = -K \frac{dh}{ds} \tag{4.3}$$

in which, dh/ds is the hydraulic gradient which is negative, since h decreases in the positive direction of the flow. Thus, flow along the three principal co-ordinate axes can be described as

$$u = -K_x \frac{\partial h}{\partial x} \tag{4.4a}$$

$$v = -K_y \frac{\partial h}{\partial y} \tag{4.4b}$$

and

$$w = -K_z \frac{\partial h}{\partial z} \tag{4.4c}$$

Here, u, v, and w are the velocity components in the x-, y-, and z-directions, respectively, and K_x, K_y, and K_z are hydraulic conductivities (coefficients of permeability) in these directions.

In Darcy's law, the velocity is proportional to the first power of the hydraulic gradient and is, therefore, applicable to laminar flows only. For a flow through porous medium, Reynolds number R_e can be expressed as

$$R_e = \frac{Vd\rho}{\mu}$$

Here, d is the representative average grain diameter which approximately represents the average pore diameter, *i.e.*, the flow dimension. ρ and μ are, respectively, the mass density and the dynamic viscosity of the flowing water. An upper limit of Reynolds number ranging between 1 and 10 has been suggested as the limit of validity of Darcy's law (4). A range rather than a unique value of R_e has been specified in view of the possible variety of grain shapes, grain-size distribution, and their packing conditions. For natural ground water motion, R_e is usually less than unity and Darcy's law is, therefore, usually applicable.

When Darcy's law is substituted in the continuity equation of motion, one obtains the equation governing the flow of water through a porous medium. The resulting equations for confined and unconfined aquifers are, respectively, as follows (5):

$$\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} + \frac{\partial^2 h}{\partial z^2} = \frac{S}{T}\frac{\partial h}{\partial t} \tag{4.5}$$

and

$$\frac{\partial^2 H^2}{\partial x^2} + \frac{\partial^2 H^2}{\partial y^2} = \frac{2n}{K}\frac{\partial H}{\partial t} \tag{4.6}$$

Here, H represents the hydraulic head in unconfined aquifer and n is the porosity of the medium. Equations (4.5) and (4.6) are, respectively, known as Boussinesq's and Dupuit's equations. Both these equations assume that the medium is homogeneous, isotropic, and water is incompressible. Equation (4.5) also assumes that large pressure variations do not occur. Equation (4.6) further assumes that the curvature of the free surface is sufficiently small for the vertical components of the flow velocity to be negligible in comparison to the horizontal component. For steady flow, Eqs. (4.5) and (4.6) become

$$\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} + \frac{\partial^2 h}{\partial z^2} = 0 \tag{4.7a}$$

$$\frac{\partial^2 H^2}{\partial x^2} + \frac{\partial^2 H^2}{\partial y^2} = 0 \tag{4.7b}$$

4.5. WELL HYDRAULICS

A well is a hydraulic structure which, if properly designed and constructed, permits economic withdrawal of water from an aquifer (6). When water is pumped from a well, the water table (or the piezometric surface in case of a confined aquifer) is lowered around the well. The surface of a lowered water table resembles a cone and is, therefore, called the *cone of depression*. The horizontal distance from the centre of a well to the practical limit of the cone of depression is known as the *radius of influence* of the well. It is larger for wells in confined aquifers than for those in unconfined aquifers. All other variables remaining the same, the radius of influence is larger in aquifers with higher transmissivity than in those with lower transmissivity. The difference, measured in the vertical direction, between the initial water table (or the piezometric surface in the confined aquifer) and its lowered level due to pumping at any location within the radius of influence is called the *drawdown* at that location. *Well yield* is defined as the volume of water discharge, either by pumping or by free flow, per unit time. Well yield per unit drawdown in the well is known as the *specific capacity* of the well.

With the continued pumping of a well, the cone of depression continues to expand in an extensive aquifer until the pumping rate is balanced by the recharge rate. When pumping and recharging rates balance each other, a steady or equilibrium condition exists and there is no further drawdown with continued pumping. In some wells, the equilibrium condition may be attained within a few hours of pumping, while in others it may not occur even after prolonged pumping.

4.5.1. Equilibrium Equations

For confined aquifers, the governing equation of flow, Eq. (4.7*a*), can be written in polar cylindrical coordinates (r, θ, z) as

$$\frac{1}{r}\left(\frac{\partial}{\partial r} r \frac{\partial h}{\partial r}\right) + \frac{\partial^2 h}{r^2 \partial \theta^2} + \frac{\partial^2 h}{\partial z^2} = 0 \tag{4.8}$$

If one assumes radial symmetry (*i.e.*, h is independent of θ) and the aquifer to be horizontal and of constant thickness (*i.e.*, h is independent of z), Eq. (4.8) reduces to

$$\frac{d}{dr}\left(r \frac{dh}{dr}\right) = 0 \tag{4.9}$$

For flow towards a well, penetrating the entire thickness of a horizontal confined aquifer, Eq. (4.9) needs to be solved for the following boundary conditions (Fig. 4.4):

(*i*) at $r = r_0$, $h = h_0$ (r_0 is the radius of influence)

(*ii*) at $r = r_w$, $h = h_w$ (r_w is the radius of well)

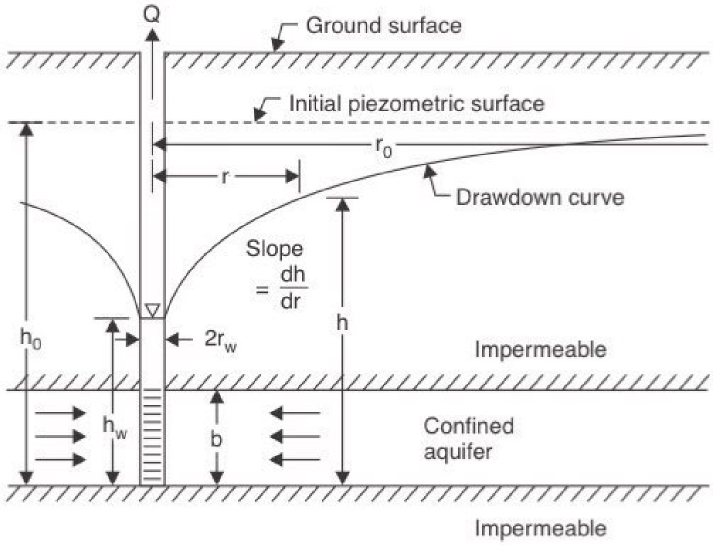

Fig. 4.4 Radial flow to a well penetrating an extensive confined aquifer

On integrating Eq. (4.9) twice with respect to r, one obtains

$$r \frac{dh}{dr} = C_1$$

and
$$h = C_1 \ln r + C_2 \tag{4.10}$$

in which C_1 and C_2 are constants of intergration to be obtained by substituting the boundary conditions in Eq. (4.10) which yields

$$h_0 = C_1 \ln r_0 + C_2$$

and
$$h_w = C_1 \ln r_w + C_2$$

Hence, $$C_1 = \frac{h_0 - h_w}{\ln (r_0/r_w)}$$

and $$C_2 = h_0 - \frac{h_0 - h_w}{\ln (r_0/r_w)} \ln r_0$$

Also, $$C_2 = h_w - \frac{h_0 - h_w}{\ln (r_0/r_w)} \ln r_w$$

Finally, $$h = h_0 - \frac{h_0 - h_w}{\ln (r_0/r_w)} \ln (r_0/r) \quad (4.11)$$

and also, $$h = h_w + \frac{h_0 - h_w}{\ln (r_0/r_w)} \ln (r/r_w) \quad (4.12)$$

Further, the discharge Q through any cylinder of radius r and height equal to the thickness of the aquifer B is expressed as

$$Q = -K(2\pi r B)\frac{dh}{dr}$$
$$= -2\pi T\left(r\frac{dh}{dr}\right)$$
$$= -2\pi TC_1$$

$$\therefore \quad Q = -2\pi T\frac{h_0 - h_w}{\ln (r_0/r_w)} \quad (4.13)$$

Thus, Eqs. (4.11) and (4.12) can be rewritten as

$$h = h_0 + \frac{Q}{2\pi T} \ln (r_0/r) \quad (4.14)$$

and $$h = h_w - \frac{Q}{2\pi T} \ln (r/r_w) \quad (4.15)$$

It should be noted that the coordinate r is measured positive away from the well and that the discharge towards the well is in the negative direction of r. Therefore, for a discharging well, Q is substituted as a negative quantity in Eqs. (4.13) through (4.15). If the drawdown at any radial distance r from the well is represented by s, then

$$s = h_0 - h = -\frac{Q}{2\pi T} \ln r_0/r \quad (4.16)$$

and the well drawdown s_w is given as

$$s_w = h_0 - h_w = -\frac{Q}{2\pi T} \ln r_0/r_w \quad (4.17)$$

For unconfined aquifers, one can similarly obtain the following equations starting from the Dupuit's equation, Eq. (4.7b):

$$H^2 = H_0^2 - \frac{H_0^2 - H_w^2}{\ln (r_0/r_w)} \ln r_0/r \quad (4.18)$$

$$H^2 = H_w^2 + \frac{H_0^2 - H_w^2}{\ln (r_0/r_w)} \ln (r/r_w) \quad (4.19)$$

$$Q = -\pi K \frac{H_0^2 - H_w^2}{\ln (r_0/r_w)} \tag{4.20}$$

$$H^2 = H_0^2 + \frac{Q}{\pi K} \ln (r_0/r) \tag{4.21}$$

$$H^2 = H_w^2 - \frac{Q}{\pi K} \ln (r/r_w) \tag{4.22}$$

Example 4.3 A well with a radius of 0.3 m, including gravel envelope and developed zone, completely penetrates an unconfined aquifer with $K = 25$ m/day and initial water table at 30 m above the bottom of the aquifer. The well is pumped so that the water level in the well remains at 22 m above the bottom of the aquifer. Assuming that pumping has essentially no effect on water table height at 300 m from the well, determine the steady-state well discharge. Neglect well losses.

Solution: From Eq. (4.20),

$$Q = -\pi K \frac{H_0^2 - H_w^2}{\ln (r_0/r_w)}$$

$$= -\frac{3.14 \times 25 \times (30^2 - 22^2)}{\ln\left(\frac{300}{0.3}\right)}$$

$$= -4729.84 \text{ m}^3/\text{day}.$$

Negative sign indicates pumping well.

4.5.2. Non-Equilibrium Equations

For an unsteady flow in confined aquifer, Eq. (4.5) can be written in polar cylindrical coordinates (r, θ, z) as

$$\frac{1}{r}\left(\frac{\partial}{\partial r} r \frac{\partial h}{\partial r}\right) + \frac{\partial^2 h}{r^2 \partial \theta^2} + \frac{\partial^2 h}{\partial z^2} = \frac{S}{T}\frac{\partial h}{\partial t} \tag{4.23}$$

which reduces to

$$\frac{\partial^2 h}{\partial r^2} + \frac{1}{r}\frac{\partial h}{\partial r} = \frac{S}{T}\frac{\partial h}{\partial t} \tag{4.24}$$

if one assumes radial symmetry and the aquifer to be horizontal and of constant thickness. The general form of solution of Eq. (4.24) is $h(r, t)$. For unsteady flow towards a well penetrating the entire thickness of a confined aquifer, Eq. (4.24) needs to be solved for the following boundary conditions:

(*i*) $h(\infty, t) = h_0$

(*ii*) $2\pi r_w B \left(K \frac{\partial h}{\partial r}\right)_{r=r_w} = -Q$ for $t > 0$ (flux condition)

$$\therefore \quad \left(r_w \frac{\partial h}{\partial r}\right)_{r=r_w} = -\frac{Q}{2\pi T}$$

which can be approximated as

$$\left(r \frac{\partial h}{\partial r}\right)_{r \to 0} = -\frac{Q}{2\pi T}$$

(*iii*) $h(r, 0) = h_0$ (initial condition).

Theis (7) obtained a solution of Eq. (4.24) by assuming that the well is replaced by a mathematical sink of constant strength. The solution is expressed as

$$s = h_0 - h = -\frac{Q}{4\pi T}\int_u^{\infty} \frac{e^{-u}}{u}\, du \tag{4.25}$$

in which $$u = \frac{r^2 S}{4Tt}$$

where, t is the time since the beginning of pumping. Equation (4.25) is also written as

$$s = -\frac{Q}{4\pi T} W(u) \tag{4.26}$$

in which, $W(u)$ is known as the well function (Table 4.2) and is expressed as a function of u in the form of the following convergent series:

$$W(u) = -0.5772 - \ln u + u - \frac{u^2}{2 \times 2!} + \frac{u^3}{3 \times 3!} - \frac{u^4}{4 \times 4!} + \ldots \tag{4.27}$$

An approximate form of the Theis equation (*i.e.*, Eq. (4.25)) was obtained by Cooper and Jacob (8) dropping the third and higher order terms of the series of Eq. (4.27). Thus,

$$s = -\frac{Q}{4\pi T}[-0.5772 - \ln u]$$

or $$s = -\frac{Q}{4\pi T}\left[\ln \frac{0.25\, Tt}{r^2 S}\right]$$

$\therefore$ $$s = -\frac{0.183\, Q}{T}\left[\log \frac{2.25\, Tt}{r^2 S}\right] \tag{4.28}$$

For values of u less than 0.05, Eq. (4.28) gives practically the same results as obtained by Eq. (4.26). Note that Q is to be substituted as a negative quantity for a pumping well.

Because of the non-linear form of Eq. (4.6), its solution is difficult. Boulton (9) has presented a solution for fully penetrating wells in an unconfined aquifer. The solution is valid if the water depth in the well exceeds 0.5 H_0. The solution is

$$s = \frac{Q}{2\pi K H_0}(1 + C_k)\, V(t', r') \tag{4.29}$$

in which, C_k is a correction factor which can be taken as zero for t' less than 5, and according to Table 4.3 for t' greater than 5 (when C_k depends only on r'). $V(t', r')$ is Boulton's well function dependent on r' and t' defined as

$$t' = \frac{Kt}{SH_0}$$

and $$r' = \frac{r}{H_0}$$

Table 4.2 Well function $W(u)$ for different values of u

u	*1.0*	*2.0*	*3.0*	*4.0*	*5.0*	*6.0*	*7.0*	*8.0*	*9.0*
× 1	0.219	0.049	0.013	0.0038	0.0011	0.00036	0.00012	0.000038	0.000012
$\times 10^{-1}$	1.82	1.22	0.91	0.70	0.56	0.45	0.37	0.31	0.26
$\times 10^{-2}$	4.04	3.35	2.96	2.68	2.47	2.30	2.15	2.03	1.92
$\times 10^{-3}$	6.33	5.64	5.23	4.95	4.73	4.54	4.39	4.26	4.14
$\times 10^{-4}$	8.63	7.94	7.53	7.25	7.02	6.84	6.69	6.55	6.44
$\times 10^{-5}$	10.94	10.24	9.84	9.55	9.33	9.14	8.99	8.86	8.74
$\times 10^{-6}$	13.24	12.55	12.14	11.85	11.63	11.45	11.29	11.16	11.04
$\times 10^{-7}$	15.54	14.85	14.44	14.15	13.93	13.75	13.60	13.46	13.34
$\times 10^{-8}$	17.84	17.15	16.74	16.46	16.23	16.05	15.90	15.76	15.65
$\times 10^{-9}$	20.15	19.45	19.05	18.76	18.54	18.35	18.20	18.07	17.95
$\times 10^{-10}$	22.45	21.76	21.35	21.06	20.84	20.66	20.50	20.37	20.25
$\times 10^{-11}$	24.75	24.06	23.65	23.36	23.14	22.96	22.81	22.67	22.55
$\times 10^{-12}$	27.05	26.36	25.96	25.67	25.44	25.26	25.11	24.97	24.86
$\times 10^{-13}$	29.36	28.66	28.26	27.97	27.75	27.56	27.41	27.28	27.16
$\times 10^{-14}$	31.66	30.97	30.56	30.27	30.05	29.87	29.71	29.58	29.46
$\times 10^{-15}$	33.96	33.27	32.86	32.58	32.35	32.17	32.02	31.88	31.76

Table 4.3 Values of C_k for $t' > 5$

r'	0.03	0.04	0.06	0.08	0.1	0.2	0.4	0.6	0.8	1	2	4
C	– 0.27	– 0.24	– 0.19	– 0.16	– 0.13	– 0.05	– 0.02	0.05	0.05	0.05	0.03	0

Values of the function V have been tabulated in Table 4.4. The approximate values of V can also be calculated as follows:

For $t' < 0.01$ and $t'/r' > 10$.

$$V \approx \ln (2t'/r')$$

For $t' < 0.01$,

$$V \approx \sin h^{-1} (t'/r') - \frac{1}{\sqrt{1+r'^2}}$$

For $t' < 0.05$,

$$V \approx \sin h^{-1} \left[\frac{1}{r'}\right] + \sin h^{-1} [t'/r'] - \sin h^{-1} \left[\frac{1+t'}{r'}\right]$$

For $t' > 5.0$,

$$V \approx \frac{1}{2} W(u)$$

in which,

$$u = \frac{r^2 n_e}{4Tt}$$

Here, n_e is the effective porosity of the aquifer.

The well equations mentioned in this section are valid only for a single well of small diameter having no storage capability and fully penetrating an extensive aquifer. The equations will be modified for the effect of partial penetration, well storage, bounded aquifers, interference of adjacent wells, and multi-layer aquifer systems.

Example 4.4 A fully penetrating artesian well is pumped at a rate Q = 1500 m^3/day from an aquifer whose storage coefficient and transmissivity are 4×10^{-4} and 0.145 m^2/min, respectively. Find the drawdowns at a distance 3 m from the production well after one hour of pumping and at a distance of 350 m after one day of pumping.

Solution:

At r = 3 m and t = 1 h,

$$u = \frac{r^2 s}{4\,Tt} = \frac{3 \times 3 \times 4 \times 10^{-4}}{4 \times 0.145 \times (1 \times 60)} = 1.03 \times 10^{-4}$$

$\therefore$

$$w(u) = 8.62$$

From Eq. (4.26)

$\therefore$

$$s = -\frac{Q}{4\,\pi T} W(u) = \frac{1500/(24 \times 60)}{4 \times 3.14 \times 0.145} \times 8.62$$

$$= 4.93 \text{ m}$$

Similarly, at r = 350 m and t = 1 day

Table 4.4 Function $V(t', r')$ for different values of t' and r'

t'	Value of r'																	
	0.001	*0.002*	*0.003*	*0.004*	*0.005*	*0.006*	*0.007*	*0.008*	*0.009*	*0.01*	*0.02*	*0.03*	*0.04*	*0.05*	*0.06*	*0.07*	*0.08*	*0.09*
0.01	2.99	2.30	1.90	1.64	1.42	1.28	1.15	1.04	0.95	0.875	0.474	0.322	0.240	0.192	0.158	0.135	0.118	0.104
0.02	3.68	2.97	2.58	2.30	2.09	1.92	1.76	1.64	1.52	1.42	0.860	0.610	0.468	0.378	0.316	0.270	0.236	0.210
0.03	4.08	3.40	3.00	2.70	2.46	2.28	2.13	2.00	1.88	1.79	1.18	0.860	0.675	0.555	0.465	0.400	0.350	0.310
0.04	4.35	3.68	3.26	2.98	2.75	2.58	2.42	2.29	2.17	2.06	1.42	1.07	0.850	0.710	0.600	0.525	0.460	0.410
0.05	4.58	3.90	3.49	3.20	2.96	2.79	2.64	2.50	2.38	2.28	1.60	1.24	1.010	0.850	0.725	0.630	0.560	0.500
0.06	4.76	4.06	3.65	3.36	3.15	2.96	2.80	2.68	2.56	2.45	1.78	1.40	1.15	0.970	0.840	0.735	0.650	0.585
0.07	4.92	4.20	3.80	3.51	3.30	3.12	2.96	2.82	2.70	2.60	1.91	1.54	1.28	1.09	0.950	0.835	0.740	0.670
0.08	5.08	4.34	3.94	3.65	3.42	3.24	3.09	2.95	2.84	2.72	2.04	1.65	1.39	1.20	1.04	0.925	0.825	0.750
0.09	5.18	4.47	4.05	3.75	3.54	3.35	3.20	3.05	2.95	2.84	2.14	1.75	1.50	1.29	1.14	1.02	0.910	0.825
0.1	5.24	4.54	4.14	3.85	3.63	3.45	3.30	3.15	3.04	2.94	2.25	1.85	1.58	1.38	1.22	1.09	0.985	0.890
0.2	5.85	5.15	4.78	4.50	4.28	4.10	3.93	3.80	3.66	3.56	2.87	2.46	2.20	1.98	1.80	1.65	1.52	1.42
0.3	6.24	5.50	5.12	4.85	4.61	4.43	4.28	4.14	4.01	3.90	3.24	2.84	2.54	2.32	2.14	1.98	1.85	1.74
0.4	6.45	5.75	5.35	5.08	4.85	4.67	4.50	4.38	4.26	4.15	3.46	3.05	2.76	2.54	2.36	2.20	2.07	1.96
0.5	6.65	6.00	5.58	5.25	5.00	4.85	4.70	4.55	4.45	4.30	3.65	3.24	2.95	2.72	2.52	2.38	2.24	2.14
0.6	6.75	6.10	5.65	5.40	5.15	4.98	4.82	4.68	4.56	4.45	3.76	3.37	3.09	2.85	2.67	2.50	2.38	2.26
0.7	6.88	6.20	5.80	5.50	5.25	5.08	4.92	4.80	4.68	4.55	3.90	3.50	3.20	2.99	2.80	2.64	2.50	2.38
0.8	7.00	6.25	5.85	5.60	5.35	5.20	5.00	4.90	4.80	4.65	3.96	3.55	3.26	3.05	2.86	2.71	2.58	2.46
0.9	7.10	6.35	6.00	5.70	5.50	5.30	5.12	5.00	4.90	4.75	4.05	3.65	3.36	3.15	2.96	2.80	2.66	2.55
1	7.14	6.45	6.05	5.75	5.55	5.35	5.20	5.05	4.95	4.83	4.10	3.74	3.45	3.22	3.04	2.90	2.75	2.64
2	7.60	6.88	6.45	6.15	5.92	5.75	5.60	5.50	5.35	5.25	4.59	4.18	3.90	3.68	3.50	3.34	3.20	3.09
3	7.85	7.15	6.70	6.45	6.20	6.00	5.85	5.75	5.60	5.50	4.82	4.42	4.12	3.90	3.72	3.57	3.45	3.31
4	8.00	7.28	6.85	6.58	6.35	6.15	6.00	5.90	5.75	5.70	4.95	4.55	4.26	4.04	3.86	3.70	3.59	3.46
5	8.15	7.35	7.00	6.65	6.50	6.25	6.10	6.00	5.85	5.80	5.05	4.68	4.40	4.19	4.00	3.85	3.71	3.60
6	8.20	7.50	7.10	6.75	6.55	6.35	6.20	6.10	5.95	5.85	5.20	4.78	4.50	4.26	4.09	3.92	3.80	3.69
7	8.25	7.55	7.15	6.85	6.62	6.40	6.30	6.20	6.05	5.95	5.25	4.85	4.58	4.35	4.18	4.00	3.90	3.78
8	8.30	7.60	7.20	6.90	6.70	6.50	6.35	6.25	6.10	6.05	5.30	4.92	4.65	4.40	4.25	4.10	3.95	3.82
9	8.32	7.65	7.25	7.00	6.75	6.55	6.40	6.30	6.15	6.10	5.35	5.00	4.70	4.49	4.30	4.15	4.00	3.90
10	8.35	7.75	7.35	7.05	6.80	6.60	6.45	6.35	6.20	6.14	5.40	5.02	4.80	4.52	4.35	4.19	4.05	3.92

(Contd.)...

Table 4.4 (Contd..)

t'	Values of r'													
	0.1	*0.2*	*0.3*	*0.4*	*0.5*	*0.6*	*0.7*	*0.8*	*0.9*	*1*	*2*	*3*	*4*	*5*
0.01	0.093	0.0430	0.0264	0.0180	0.0132	0.0100	0.0078	0.0062	0.0049	0.0040	0.00057	0.00015		
0.02	0.187	0.0865	0.0530	0.0365	0.0268	0.0205	0.0160	0.0125	0.0100	0.0081	0.00118	0.00020		
0.03	0.278	0.130	0.0800	0.0550	0.0405	0.0310	0.0240	0.0190	0.0150	0.0122	0.00184	0.00032		
0.04	0.368	0.174	0.107	0.0735	0.0540	0.0415	0.0322	0.0255	0.0202	0.0165	0.00244	0.00043		
0.05	0.450	0.215	0.133	0.0920	0.0675	0.0520	0.0400	0.0320	0.0255	0.0206	0.00305	0.00055		
0.06	0.530	0.257	0.160	0.110	0.0810	0.0610	0.0478	0.0380	0.0305	0.0250	0.00365	0.00065		
0.07	0.610	0.298	0.186	0.130	0.0950	0.0725	0.0565	0.0450	0.0360	0.0292	0.00430	0.00078		
0.08	0.680	0.340	0.214	0.148	0.108	0.0825	0.0645	0.0510	0.0412	0.0336	0.00500	0.00090		
0.09	0.750	0.378	0.236	0.164	0.122	0.0930	0.0730	0.0585	0.0470	0.0380	0.00570	0.00105		
0.1	0.815	0.415	0.260	0.180	0.134	0.103	0.0805	0.0640	0.0515	0.0420	0.00635	0.00118		
0.2	1.32	0.750	0.500	0.359	0.268	0.208	0.165	0.132	0.107	0.0880	0.0145	0.00278		
0.3	1.64	1.02	0.700	0.515	0.392	0.308	0.246	0.200	0.164	0.135	0.0238	0.00490		
0.4	1.86	1.22	0.870	0.650	0.510	0.405	0.328	0.268	0.220	0.182	0.0350	0.00750	0.00160	0.00038
0.5	2.03	1.37	1.00	0.770	0.610	0.490	0.400	0.330	0.275	0.230	0.0450	0.0104	0.00240	0.00056
0.6	2.16	1.49	1.12	0.875	0.700	0.570	0.468	0.390	0.325	0.276	0.0580	0.0138	0.00320	0.00080
0.7	2.28	1.60	1.22	0.965	0.775	0.640	0.525	0.445	0.375	0.320	0.0715	0.0175	0.00425	0.00108
0.8	2.36	1.69	1.30	1.04	0.850	0.715	0.600	0.500	0.425	0.364	0.0840	0.0212	0.00525	0.00140
0.9	2.45	1.75	1.38	1.11	0.920	0.775	0.650	0.550	0.475	0.404	0.0980	0.0260	0.00630	0.00165
1	2.54	1.85	1.45	1.18	0.975	0.825	0.700	0.595	0.510	0.444	0.113	0.0310	0.00840	0.00235
2	2.97	2.29	1.88	1.60	1.38	1.22	1.07	0.950	0.840	0.750	0.259	0.0950	0.0330	0.0115
3	3.20	2.50	2.10	1.82	1.60	1.42	1.28	1.15	1.05	0.960	0.388	0.165	0.0700	0.0275
4	3.36	2.66	2.25	1.97	1.75	1.58	1.42	1.30	1.20	1.10	0.495	0.235	0.112	0.0535
5	3.49	2.78	2.38	2.09	1.87	1.69	1.54	1.42	1.30	1.21	0.580	0.300	0.150	0.0715
6	3.59	2.90	2.47	2.18	1.95	1.78	1.65	1.52	1.40	1.30	0.660	0.360	0.195	0.0990
7	3.66	2.96	2.55	2.25	2.04	1.85	1.70	1.58	1.48	1.38	0.730	0.415	0.230	0.125
8	3.74	3.00	2.60	2.32	2.11	1.94	1.79	1.66	1.55	1.44	0.790	0.465	0.272	0.155
9	3.80	3.09	2.67	2.39	2.17	2.00	1.85	1.72	1.60	1.50	0.850	0.515	0.307	0.182
10	3.84	3.12	2.74	2.45	2.24	2.05	1.90	1.77	1.65	1.55	0.890	0.550	0.340	0.210

$$u = \frac{(350)^2 \times 4 \times 10^{-4}}{4 \times 0.145 \times 24 \times 60} = 5.87 \times 10^{-2}$$

$\therefore$ $$w(u) = 2.316$$

and $$s = \frac{1500/(24 \times 60)}{4\,\pi \times 0.145} \times 2.316$$

$$= 1.32 \text{ m.}$$

4.5.3. Well Interference

If the zone of influence of two adjacent wells overlap (*i.e.,* the wells are spaced at distances smaller than the sum of their radii of influence), the wells affect each other's drawdown and discharge. This effect is due to what is known as well interference. As a result of well interference, even though the total output (*i.e.,* the discharge) of a multiple well system increases, the efficiency of each well (measured in terms of the discharge per unit drawdown) of the system decreases. Since the equation of flow in a confined aquifer is a linear one, one can use the principle of superposition to obtain the resulting drawdown at a point in a well field in which number of wells are being pumped simultaneously. This means, if s_i is the total drawdown at i^{th} observation well on acount of pumping of N wells located in the well field, then

$$s_i = \sum_{j=1}^{N} s_{ij} \tag{4.30}$$

in which, s_{ij} is the drawdown at i^{th} observation well on account of pumping of j^{th} well as if there were no interference effects.

Considering steady flow conditions for two wells in a confined aquifer located distance B apart, the drawdown in the two wells s_{w1} and s_{w2} can be expressed as

$$s_{w1} = \frac{Q_1}{2\,\pi T} \ln \frac{r_0}{r_w} + \frac{Q_2}{2\,\pi T} \ln \frac{r_0}{B}, \tag{4.31}$$

$$s_{w2} = \frac{Q_1}{2\,\pi T} \ln \frac{r_0}{B} + \frac{Q_2}{2\,\pi T} \ln \frac{r_0}{r_w} \tag{4.32}$$

If $Q_1 = Q_2 = Q$, then

$$s_{w1} = s_{w2} = h_0 - h_w = \frac{Q}{2\,\pi T} \ln \frac{r_0^{\,2}}{Br_w}$$

This means,

$$\frac{Q}{h_0 - h_w} = \frac{2\,\pi T}{\ln \dfrac{r_0^{\,2}}{Br_w}} \tag{4.33}$$

Since,

$$\ln \frac{r_0^{\,2}}{Br_w} > \ln \frac{r_0}{r_w},$$

it is obvious that the efficiency of an individual well has reduced. On the other hand, Eq. (4.33) can also be written as

$$\frac{2\,Q}{h_0 - h_w} = \frac{2\,\pi T}{\ln\,[r_0/(Br_w)^{0.5}]} \tag{4.34}$$

Since $(Br_w)^{0.5} >> r_w$, the value of $(h_0 - h_w)$ is relatively less for a discharge of 2 Q compared to the value of $(h_0 - h_w)$ when only a single well were to pump a discharge of 2 Q. This shows that the efficiency of a multiple well system is higher compared to that of a single well. But, the efficiency of an individual well in a multiple well system is reduced.

4.5.4. Wells Near Aquifer Boundaries

The equations for radial flow towards well assume infinite extent of aquifer. However, in practice, there would be situations when a well may be located near hydrogeologic boundaries and the derived equations would not be applicable as such. The influence of such boundaries on ground water movement can be determined by the image well method.

The image well method assumes straight line boundaries and replaces the real bounded field of flow with a fictitious field of flow with simple boundary conditions such that the flow patterns in the two cases are the same. Consider a pumping well located in the vicinity of a stream (*i.e.*, recharge or permeable boundary). Obviously, the drawdown at the stream on account of pumping well would be zero. This real flow system is now assumed to be replaced with a fictitious flow system, Fig. 4.5. In addition to the real pumping well, the fictitious flow system has, in place of the boundary, an image well (which is a recharging one *i.e.*, the one which pumps water into the aquifer) with the same capacity as that of the real well but located across the real boundary on a perpendicular thereto and at the same distance as the real well from the boundary. Obviously, this fictitious system would result in zero drawdown at the location of the boundary. This means that the flow condition of the real flow system is satisfied by the flow condition of the fictitious flow system. If the boundary is a barrier (*i.e.*, impermeable) boundary, the method remains the same but the image well is also a pumping well. It should be noted that in the fictitious system the real and image wells operate simultaneously and the drawdowns can be obtained by considering the fictitious system as a multiple well system. When an aquifer is delimited by two or more boundaries, the effect of the other boundaries on each of the image wells is also to be considered. As a result, there would be several images, Fig. 4.6. When the image wells are too far from the region of interest, their influence on the flow system in the region of interest is negligible and are, therefore, not included in the computations.

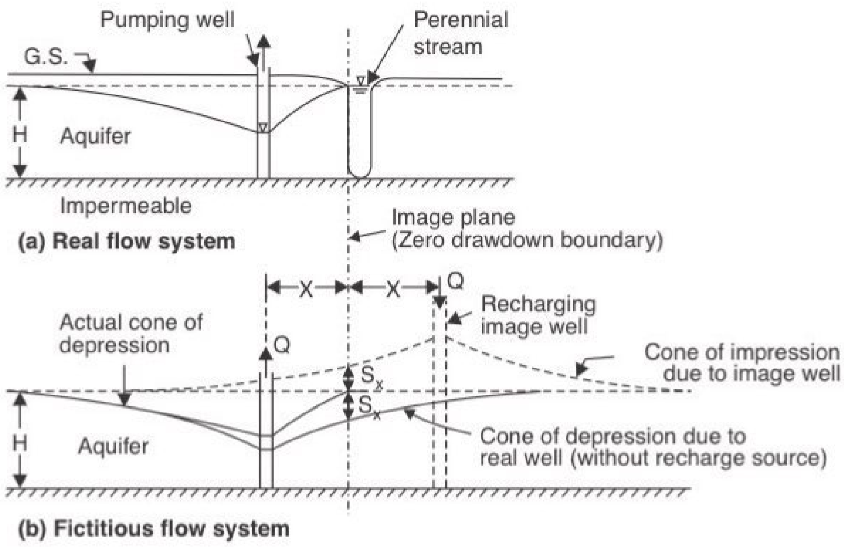

Fig. 4.5 Simulation of recharge boundary

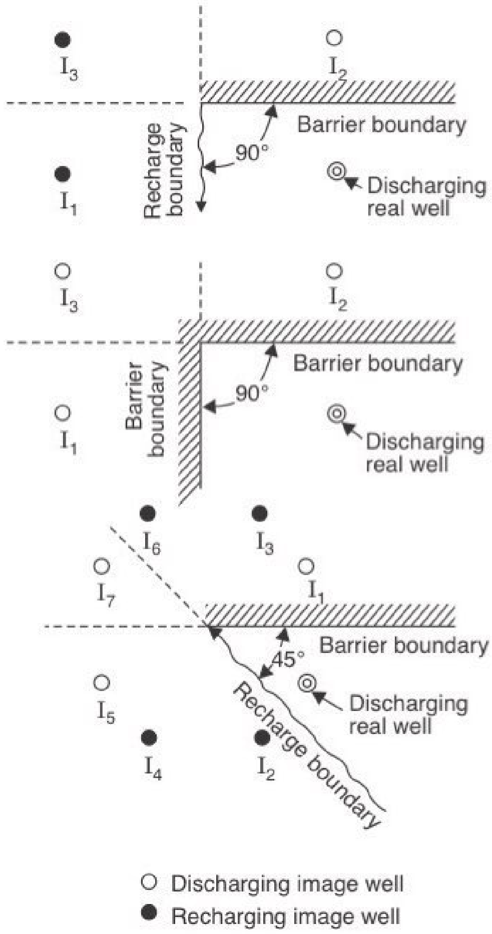

Fig. 4.6 Image well system for different pairs of boundaries

4.6. GROUND WATER EXPLORATION

It is known that everywhere on the earth there is some water under the surface. Ground water planners, however, need to know whether the conditions of the available ground water would permit its economic withdrawal through wells. The purpose of ground water exploration is to delineate the water-bearing formations, estimate their hydrogeologic characteristics and determine the quality of water present in these formations. Some of the exploration methods are briefly discussed in the following paragraphs.

4.6.1. Remote Sensing

Aerial photography, imaging (infra-red and radar) and low frequency electromagnetic aerial methods are included in the "remote sensing" methods of ground water exploration.

Valuable information associated with precipitation, evapotranspiration, interception, infiltration, and runoff can be inferred from aerial photographs by mapping the water area, geology and soil types, seepage areas, vegetation cover, and many other features (10). Satellite photographs can also be used for this purpose.

Recent developments in the nonvisible portion of the electromagnetic spectrum have resulted in several imaging techniques which are capable of mapping earth resources. Infrared imagery is sensitive to the differential head capacity of the ground and can map soil moisture, ground water movement, and faults (11). Radar imagery works in the 0.01–3 m wavelength range and can penetrate vegetation cover to provide subsurface information, such as soil moisture at shallow depths (12).

Buried subsurface channels and salt water intrusion fronts can be successfully located by using recently developed aerial electromagnetic exploration methods which operate in the frequency range of 3.0 to 9 kHz (13).

4.6.2. Surface Geophysical Methods

Surface geophysical methods reveal specific details of the physical characteristics of the local subsurface environment. This information can be interpreted suitably for the purpose of delineating the pre-glacial drainage pattern, mapping the location and extent of buried permeable deposits, direct exploration for ground water, and mapping of freshwater and salt water contact (14). The electrical resistivity method and seismic refraction method are the surface geophysical methods commonly used for ground water exploration.

(*i*) ***Electrical Resistivity Method***

The electrical resistivity of a rock depends on porosity, salinity of the fluid in the pore spaces, straightness or tortuosity of the interconnected pore spaces, presence of solid conductors,

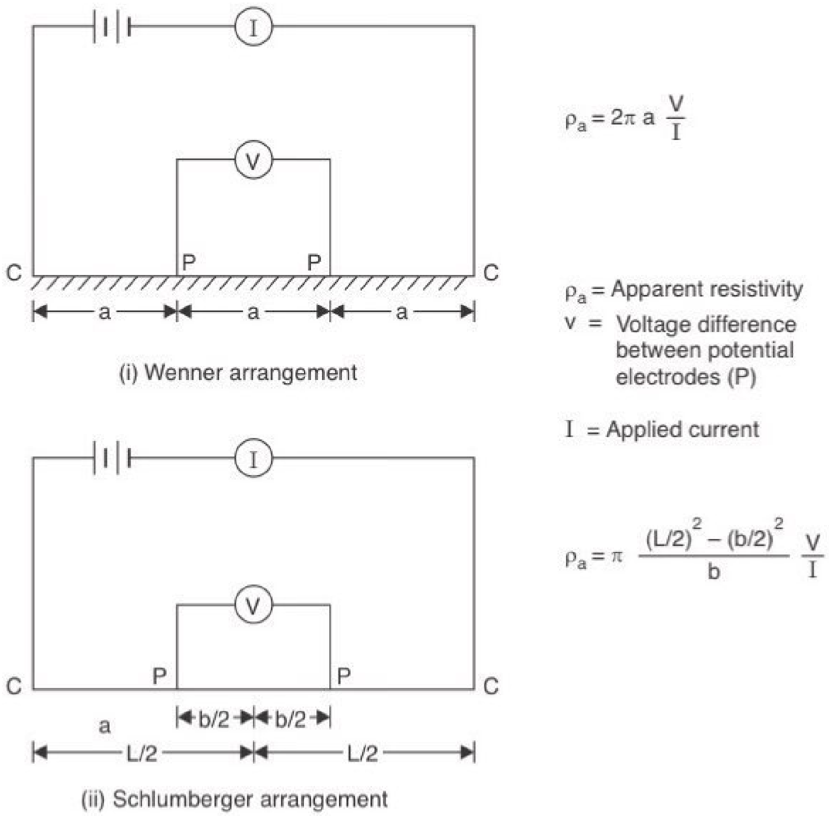

Fig. 4.7 Electrode arrays for electrical resistivity method

such as clays or metallic minerals, and temperature (2). In the electrical resistivity method, electrical current is injected into the ground through two metal stakes (electrodes) and the resulting voltage between two other metal stakes is measured. The depth of measurement is decided by the distance and the arrangement pattern of the four electrodes (Fig. 4.7) and the standard calibration curves. The changes in the electrical resistance of different earth layers are thus determined. Table 4.5 lists a typical order of values of resistivity for some common soils. Using the table and the plot of electrical resistivity versus depth, one can determine the type of subsurface layers at different depths. The electrical resistivity would vary with the salinity of the water included in the pores of earth material. Therefore, one should be careful in interpreting the results. It is advisable to prepare tables, similar to Table 4.5, or histograms of the resistivity for different regions and use these for the interpretation of resistivity measurements.

Table 4.5 Typical values of electrical resistivity for some soils (6)

Earth material	*Electrical resistivity (ohm-metres)*
Clay	1 – 100
Loam	4 – 40
Clayey soil	100 – 380
Sandy soil	400 – 4000
Loose sand	1000 – 180,000
River sand and gravel	100 – 4000
Chalk	4 – 100
Limestones	40 – 3000
Sandstones	20 – 20,000
Basalt	200 – 1000
Crystalline rocks	10^3 – 10^6

(*ii*) *Seismic Refraction Method*

This geophysical method employs seismic waves to determine variations in the thickness of the unconfined aquifer and the zone where the most permeable strata are likely to exist. The method is based on the velocity variation of artificially generated seismic waves in the ground. Seismic waves are generated either by hammering on a metal plate, or by dropping a heavy ball, or by using explosives. The time between the initiation of a seismic wave on the ground and its first arrival at a detector (seismometre) placed on the ground is measured. For the seismic refraction method, one is interested only in the arrival of the critically refracted ray, *i.e.* the ray which encounters the boundary at such an angle that when it refracts in the lower medium, it travels parallel to the boundary at a higher velocity (2). The critically refracted ray travelling along the boundary radiates wavefronts in all directions and some of which return to the surface (Fig. 4.8). Using the appropriate formulas and the time-distance graph, one can determine the depth of the bedrock. Some representative values of refracted seismic wave velocities in different soils are given in Table 4.6. This method is more precise than the electrical resistivity method in the determination of the depth to bedrock (2). The depth of

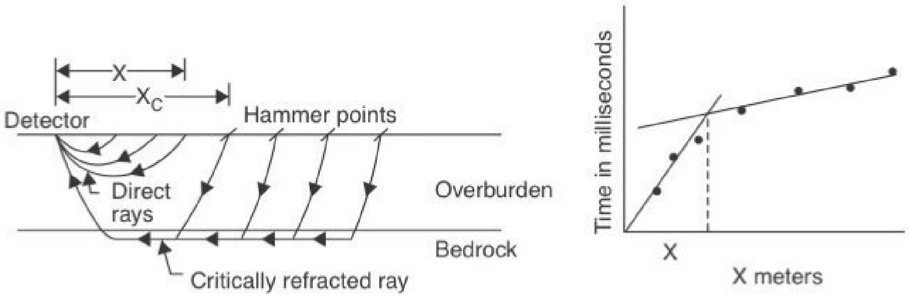

Fig. 4.8 Seismic-refracted rays and time-distance graph

Table 4.6 Representative values of velocity of seismic refracted waves in some soils (15)

Material	*Velocity (m/s)*
Gravel, rubble or dry sand	457–915
Wet sand	610–1830
Clay	915–2740
Water (depnding on temperature and salinity)	1430–1680
Sea water	1460–1520
Sandstone	1830–3960
Shale	2740–4270
Chalk	1830–3960
Limestone	2130–6100
Salt	4270–5180
Granite	4570–5790
Metamorphic rocks	3050–7010

water table in sand gravel formation can also be determined accurately because of the sudden change in seismic velocity at the water table. One important requirement for the seismic refraction method to give accurate results is that the formations must be successively denser with increasing depths.

4.6.3. Well Logging Methods

Surface methods of ground water exploration do not give exact quantitative information about the subsurface environment. Quantitative information about subsurface strata can only be obtained by subsurface investigations which are conducted by personnel working on the surface and the equipment being lowered underground. The equipment extending into the ground measures one of several geophysical quantities, such as electrical resistivity, self-potential, temperature, gamma rays, and so on. Based on these measurements, well logs are prepared. For obtaining electrical resistivity log, one or more electrodes suspended on a conductor cable are lowered into a borehole filled with drilling fluid (6). An electric current is passed between these electrodes and other electrodes placed on the ground. The logging instrument measures the resistance to a flow of current between the electrodes. Thus the electrical resistivity is measured at different depths. The resistivity of any stratum depends primarily on its characteristics and the mineral content of water contained in the stratum.

Self potentials (or spontaneous potentials) are naturally-occurring electrical potentials which result from chemical and physical changes at the contacts between different types of subsurface geologic materials (6). For measuring the self potential at any depth, an electrode is lowered into an uncased borehole filled with drilling fluid by means of an electric cable connected to one end of a millivoltmeter. The other end of this millivoltmeter is connected to a ground terminal at the surface which is usually placed in a mud pit. No external source of current is required.

In gamma logging, natural radiation coming from different strata encountered in the borehole is measured. Such a log can yield qualitative information about subsurface strata.

4.6.4. Test Drilling

All geophysical exploration methods – surface as well as subsurface – and remote sensing methods are quicker and economic but yield results which may be interpreted in more than one way. Test drilling, however, provides the most positive information about the subsurface conditions. Test drilling can predict the true geohydrologic character of subsurface formations by drilling through them, obtaining samples, recording geologic logs, and conducting aquifer tests (2). The following data are usually obtained in test drilling:

(*i*) Identification, location, and elevation of the site of each hole,

(*ii*) Geologic log of the strata penetrated,

(*iii*) Representative samples of strata penetrated,

(*iv*) Depth to static water level in each permeable stratum, and

(*v*) Water quality samples and aquifer test data from water-bearing formations.

Rotary drilling and cable tool drilling are commonly used methods of drilling wells. The rotary drilling method is fast and is the most economical method of drilling wells in unconsolidated formations. However, accurate logging of cuttings is relatively difficult and the depth of water level cannot be predicted accurately unless electric logs have been taken for this purpose. Care should be taken in distinguishing between valid cuttings carried in mud suspension and the cuttings which have been delayed in reaching the surface. Cable tool drilling is suitable for drilling to moderate depths. Sampling of geologic materials is relatively more accurate and presents fewer difficulties. Cable tool drilling is, however, a more time-consuming method.

A good lithologic well log presents variation in the geohydrologic character of subsurface formation with depth and also the depth of the water table.

4.7. PUMPING TESTS (Or AQUIFER TESTS)

Aquifer characteristics and its performance can be best described by its hydraulic conductivity, transmissivity, and storativity. These quantities can be determined by analysing the data collected during aquifer tests or pumping tests. Measurements during an aquifer test include water levels at observation wells (before the start of pumping, at intervals during pumping, and for some time after pumping), the discharge rate, and the time of any variation in the discharge rate (2).

If the observations correspond to equilibrium conditions, one can use Eq. (4.16) for confined aquifers and Eq. (4.21) for unconfined aquifers to determine the hydraulic conductivity. Thus, for two observation wells located at distances r_1 and r_2 ($r_2 > r_1$) from the pumping well, Eq. (4.16) yields

$$K = -\frac{Q \log (r_2/r_1)}{2.73\, B\, (h_2 - h_1)} \tag{4.35}$$

in which, Q is negative for the pumping well. Similarly, Eq. (4.21) would yield

$$K = -\frac{Q \log (r_2/r_1)}{1.366\, (H_2^{\,2} - H_1^{\,2})} \tag{4.36}$$

For non-equilibrium conditions in confined aquifer, Eq. (4.28) would yield

$$T = \frac{0.183\, Q}{(s_2 - s_1)} \log \frac{t_2}{t_1} \tag{4.37}$$

Here, s_1 and s_2 are the drawdowns in an observation well (r distance away from the pumping well) at two different times t_1 and t_2 (from the beginning of pumping), respectively. If t_2 is chosen as 10 t_1 and $s_2 - s_1$ for this case be denoted by Δs, Eq. (4.37) is reduced to

$$T = \frac{0.183\, Q}{\Delta s} \tag{4.38}$$

Having known T, the storativity S can be determined from Eq. (4.28) by substituting suitable values of t and s obtained from the time-drawdown graph as illustrated in the following example.

Example 4.5 A well pumps water at a rate of 2500 m^3/day from a confined aquifer. Drawdown measurements in an observation well 120 m from the pumping well are as follows:

Time since pump started in minutes	*Drawdown s in metres*	*Time since pump started in minutes*	*Drawdown s in metres*
1	0.05	14	0.40
1.5	0.08	18	0.44
2	0.12	24	0.48
2.5	0.14	30	0.52
3	0.16	50	0.61
4	0.20	60	0.64
5	0.23	80	0.68
6	0.27	100	0.73
8	0.30	120	0.76
10	0.34	150	0.80
12	0.37		

Determine the aquifer characteristics S and T assuming that Eq. (4.28) is valid.

Solution:

From the time-drawdown graph (Fig. 4.9)

$$\Delta s = 0.39 \text{ m}$$

Using Eq. (4.38),

$$T = \frac{0.183\,(2500)}{0.39} = 1173.1 \text{ m}^2\text{/day}$$

Substituting $s = 0.74$ m for $t = 100$ min $= 0.07$ day in Eq. (4.28)

$$0.73 = \frac{0.183\,(2500)}{1173.11} \log \frac{2.25\,(1173.1)\,(0.07)}{(120)^2 S}$$

$$\therefore \qquad S = 1.72 \times 10^{-4}$$

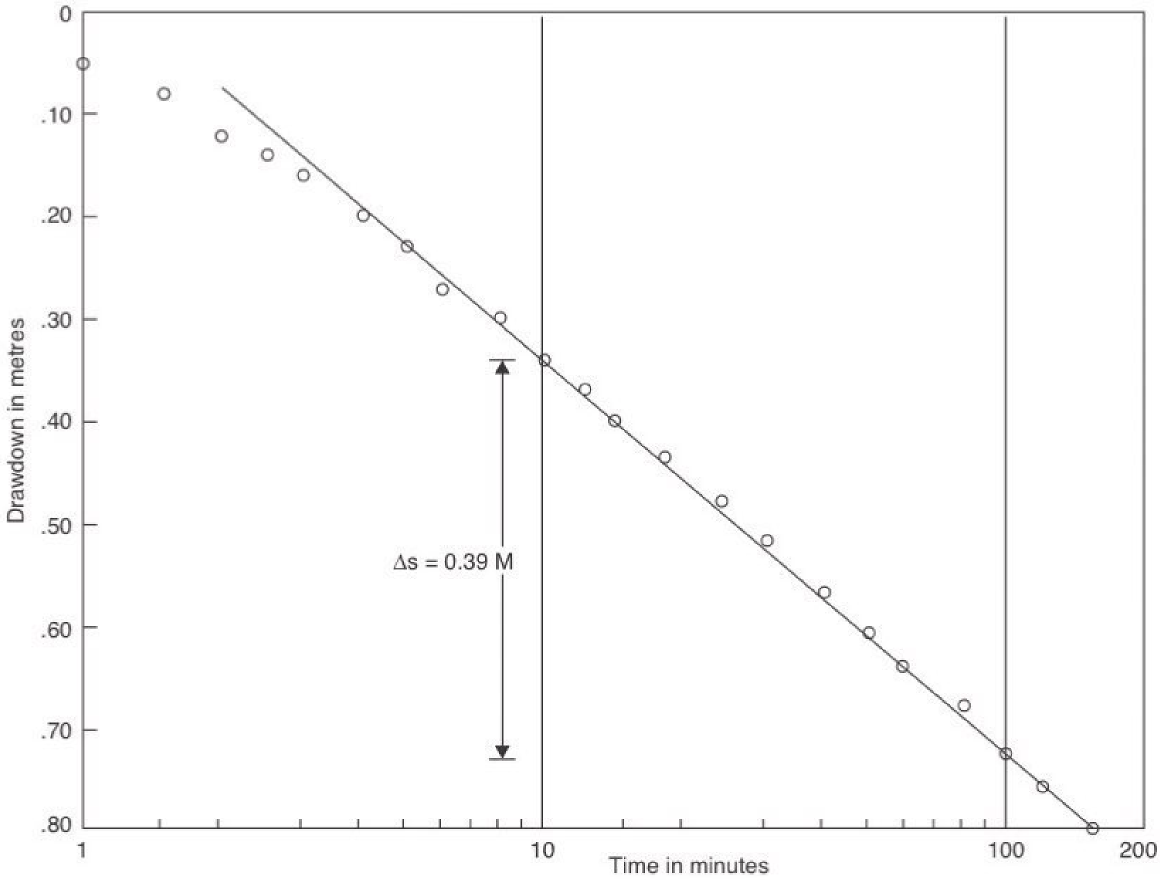

Fig. 4.9 Time-drawdown graph (Example 4.5)

4.8. DESIGN OF WATER WELLS

Well design is the process of specifying the physical materials and dimensions for various well components. The main objectives of well design are (6):

(*i*) To obtain the highest yield with a minimum drawdown consistent with aquifer capability and well requirement,

(*ii*) To obtain good quality water with proper protection from contamination,

(*iii*) To obtain sand-free water.

(*iv*) To ensure long life (30–40 years) of well, and

(*v*) To have reasonable installation, maintenance, and operation costs.

The designer needs the following hydrogeologic information for making the design (6):

(*i*) Stratigraphic information concerning the aquifer and overlying formations,

(*ii*) Transmissivity and storage coefficient of the aquifer,

(*iii*) The present and long-term water balance (*i.e.,* inflow and outflow) conditions in the aquifer,

(*iv*) Grain size analyses of unconsolidated aquifer materials and identification of rocks and minerals, and

(*v*) Water quality.

A water well has two main components – the casing and the intake portion. The casing serves as a vertical conduit for water flowing upward and also houses the pumping equipment. Some of the borehole length may, however, be left uncased if the well is constructed in consolidated rock. The intake portion in unconsolidated and semi-consolidated aquifers is usually screened. The well screen prevents fine aquifer material from entering the well with water and also serves to retain the loose formation material. In consolidated rock aquifer, the intake portion of the well may simply be an open borehole drilled into the aquifer.

Standard design procedure for a water well involves the following steps:

(*i*) Selection of strata to be screened,

(*ii*) Design of well casing and housing pipe, and

(*iii*) Design of well screen.

Before starting a well design project it is worthwhile for the designer to study the design, construction, and maintenance of other wells in the area. The design practices may vary in different regions because of the hydrogeologic conditions.

4.8.1. Selection of Strata to be Screened

The samples collected during drilling are sieve-analysed and a lithologic well log is prepared. This log describes the characteristics (type of material, size distribution, values of d_{10} or d_{17}, d_{50}, d_{60}, *etc.*, and uniformity coefficient d_{60}/d_{10}) of different subsurface strata. The lithologic log helps determine the thickness and permeability of each aquifer. The aquifers to be screened are thus decided.

4.8.2. Design of Well Casing and Housing Pipe

The well casing should meet the following requirements (16):

(*i*) It should have a smooth exterior to minimise frictional resistance between the casing and the subsurface formations.

(*ii*) It should be of adequate size to permit the passage of drilling tools, operation of well development equipment, and installation of pumps. Its size must also assure the uphole velocity of 1.5 m/s or less so that the head loss is small.

(*iii*) The walls of the casing pipe must be of sufficient thickness and suitable material to resist stresses and corrosive action of ground water environment. The life of the casing pipe should be about 30 to 40 years after its installation. Cupronickel alloys, copper-bearing steel, stainless steel, P.V.C. pipes and fibre glass-reinforced epoxy pipes are the desirable types for casing material.

(*iv*) The field joints of the casing pipe must be leak-proof and have adequate strength.

The casing pipe, when used as a housing pipe, should have sufficiently large diameter at the housing elevation to accommodate the pump with enough clearance for its installation and operation. The housing pipe should have its diameter at least 5.0 cm greater than the nominal diameter of the pump and is set a few metres below the lowest drawdown level taking into account seasonal fluctuations and future development of ground water in the area. Table 4.7 presents recommended sizes of casing (*i.e.*, well diameter) for different well yields.

Table 4.7 Recommended well diameters for different pumping rates (6)

Anticipated pumping rate (m^3/day)	*Nominal size of pump bowls (mm)*	*Optimum size of well casing (mm)*	*Smallest size of well casing (mm)*
Less than 540	102	152 ID	127 ID
410–950	127	203 ID	152 ID
820–1910	152	254 ID	203 ID
1640–3820	203	305 ID	254 ID
2730–5450	254	356 OD	305 OD
4360–9810	305	406 OD	356 OD
6540–16400	356	508 OD	406 OD
10900–20700	406	610 OD	508 OD
16400–32700	508	762 OD	610 OD

4.8.3. Design of Well Screen

The design of a well screen (*i.e.*, its length, slot, open area, diameter, and material) is the most important aspect of a well design. The basic requirements of a well screen are as follows (16):

(*i*) It should be corrosion resistant,

(*ii*) It should be strong enough to prevent collapse,

(*iii*) It should prevent excessive movement of sand into the well, and

(*iv*) It should have minimum resistance to the flow of water into the well.

4.8.3.1. Length of Well Screen

The intake portion of a well must, obviously, be placed in the zones of the maximum hydraulic conductivity. Such zones are determined by interpreting the lithologic log, visual inspection and sieve analysis of the samples collected during drilling, laboratory tests for hydraulic conductivity and the results of pumping tests. The optimum length of the well screen depends primarily on the nature of the aquifer stratification and the permissible drawdown.

In the case of a homogeneous unconfined aquifer of thickness less than 45 m the screening of the bottom one-third to one-half of the aquifer is recommended (6). In thick and deep aquifers, however, as much as 80 per cent of the aquifer may be screened to obtain a higher specific capacity and greater efficiency even though the resulting yield may be less. These guidelines are applicable to non-homogeneous unconfined aquifers also. However, screen sections are positioned in the most permeable layers of the lower portions of the aquifer (leaving depth of about 0.3 m at the upper and lower ends of the screen to prevent finer material of the transition zone from moving into the well) so that maximum drawdown is available. Wherever possible, the total screen length should be approximately one-third of aquifer thickness.

For homogeneous confined aquifers, the central 80 to 90 percent of the aquifer thickness should be screened assuming that the water level in the well would always be above the upper boundary of the aquifer. In case of non-homogeneous confined aquifer, 80 to 90 per cent of the most permeable aquifer layers should be screened.

If the effective size of two strata are the same, the stratum with lower uniformity coefficient (*i.e.,* relatively poorly graded) is more permeable and should, therefore, be screened.

4.8.3.2. Well-Screen Slot Openings

Well screen slot openings primarily depend on the size distribution of the aquifer material and also on whether the well is naturally developed or filter-packed (*i.e.,* artificially gravel-packed). Wells in aquifers with coarse-grained (d_{10} > 0.25 mm) and non-homogeneous material can be developed naturally. But wells in aquifers with fine-grained and homogeneous material are best developed using a filter pack (or gravel pack) outside the well screen.

In a naturally developed well, the screen slot size is selected so that most of the finer aquifer materials in the vicinity of the borehole are brought into the screen and pumped from the well during development. The process creates a zone of graded formation materials extending 0.3 to 0.6 m outward from the screen (6). The slot size for the screen of such wells can be selected from Table 4.8.

Table 4.8 Selection of slot size for well screen (17)

Uniformity coefficient of the aquifer being tapped	*Condition of the overlying material*	*Slot size in terms of aquifer material size*
> 6	fairly firm; would not easily cave in	d_{70}
> 6	soft; would easily cave in	d_{50}
= 3	fairly firm; would not easily cave in	d_{60}
= 3	soft; would easily cave in	d_{40}

If more than one aquifer is tapped, and the average size of the coarsest aquifer is less than four times the average size of the finest aquifer, the slot size should correspond with the finest aquifer. Otherwise, slot size must vary and correspond with the sizes of aquifer material (16). A more conservative slot size should be selected if: (*i*) there is some doubt about the reliability of the samples, (*ii*) the aquifer is thin and overlain by fine-grained loose material, (*iii*) the development time is at a premium, and (*iv*) the formation is well-sorted. Under these conditions, slot sizes which will retain 40 to 50 per cent of the aquifer material (*i.e.,* d_{60} to d_{50}) should be preferred (6).

In filter-packed wells, the zone in the immediate vicinity of the well screen is made more permeable by removing some formation material and replacing it with specially graded material. This filter pack or gravel pack separates the screen from the aquifer material and increases the effective hydraulic diameter of the well. A filter pack is so designed that it is capable of retaining 90 per cent of the aquifer material after development. Well screen openings should be such that they can retain 90 per cent of the filter pack material (6). The filter pack material must be well graded to yield a highly porous and permeable zone around the well screen. The uniformity coefficient of the filter pack should be 2.0 or less so that there is less segregation during placing and lower head loss through the pack. The filter pack material should be clean and well-rounded. Clean material requires less development time and also results in little loss of material during development. Well-rounded grains make the filter pack more permeable which reduces drawdown and increases the yield. Further, the filter pack must contain 90 to 95% quartz grains so that there is no loss of volume caused by the dissolution of materials. For minimum head loss through the filter pack and minimum sand movement, the pack-aquifer ratio (*i.e.*, the ratio of the average size of the filter pack material to the average size of the aquifer material) should be as follows (16):

	Pack-aquifer Ratio
(*i*) Uniform aquifer with uniform filter pack	9–12.5
(*ii*) Non-uniform aquifer with uniform filter pack	11–15.5

The thickness of the filter pack designed in this manner should be between 15 and 20 cm.

4.8.3.3. Open Area of Well-Screen

For head loss through the well screen to be minimum, Peterson *et al.* (18) have suggested that the value of the parameter $C_c A_p L/D$ should be greater than 0.53. Here, C_c is the coefficient of contraction for the openings, A_p the ratio of the open area to the total surface area of the screen, L the screen length, and D is the diameter of well screen. Theoretical studies conducted at the UP Irrigation Research Institute have shown that the parameter $C_c\, C_v\, A_p\, L/D$ should be greater than 1.77. Here, C_v is the coefficient of velocity. A factor of safety of 2.5 is further recommended by Sharma and Chawla (16). This means that $C_c\, C_v\, A_p\, L/D$ should be greater than 4.42.

4.8.3.4. Diameter of Well Screen

The screen diameter should be such that there is enough open area so that the entrance velocity of water generally does not exceed the design standard of 3 cm/s (6). Table 4.9 gives values of the optimum diameter for different values of the yield and hydraulic conductivity of the aquifer. These values have been worked out considering the cost of screens, cost of boring and the running expenses (16). USBR's recommended values have also been given in Table 4.9.

Table 4.9 Optimum diameter of well screen (16, 19)

Well discharge (m^3/s)	*Optimum diameter of well screen in cm for hydraulic conductivity equal to*			*USBR's recommended value of well screen diameter (cm)*
	0.04 cm/s	*0.09 cm/s*	*0.16 cm/s*	
0.04	15	18	22	25
0.08	20	25	30	30
0.12	23	28	33	35
0.16	25	30	35	40

4.8.3.5. Entrance Velocity

The entrance velocity of water moving into the well screen should be kept below a permissible value which would avoid movement of fine particles from the aquifer and filter pack to the well. The permissible entrance velocity depends on the size distribution and the granular structure of the aquifer material, the chemical properties of the ground water and shape of the screen openings. Its exact evaluation is difficult. The permissible entrance velocity is usually taken as 3 cm/s for the design of the well screen (6, 16).

4.8.3.6. Well Screen Material

Four factors govern the choice of material used for the construction of a well screen. These are: (*i*) water quality, (*ii*) presence of iron, (*iii*) strength requirements of screen, and (*iv*) cost of screen. Quality analysis of ground water usually shows that the water is either corrosive or incrusting. Corrosive water is usually acidic and contains dissolved oxygen and carbon dioxide which accelerate the corrosion. Corrosion may further increase due to higher entrance velocities. Incrustation is caused due to precipitation of iron and manganese hydroxides and other materials from water. It is, therefore, important to use corrosion-resistant materials for the fabrication of a well screen. The following alloys (in decreasing order of their ability to resist corrosion) or their suitable variations are used for the fabrication of well screens (16).

(*i*) Monel alloy (or Monel metal) (70% nickel and 30% copper)

(*ii*) Cupro-nickel (30% nickel and 70% copper)

(*iii*) Everdur A alloy (96% copper, 3% silicon and 1% manganese)

(*iv*) Stainless steel (74% low carbon steel, 18% chromium and 8% nickel)

(*v*) Silicon red brass (83% copper, 1% silicon and 16% zinc)

(*vi*) Anaconda brass (or Gilding metal) (85% copper and 15% zinc)

(*vii*) Common yellow brass (67% copper and 33% zinc)

(*viii*) Armco iron (99.84% pure iron)

(*ix*) Low carbon steel

(*x*) Ordinary cast iron.

4.9. MEHODS OF WELL CONSTRUCTION

The operations involved in well construction are drilling, installing the casing, placing a well screen and filter pack, and developing the well to ensure maximum sand-free water yield. Shallow wells, generally less than about 15 m deep, are constructed by digging, boring, driving or jetting. Deep wells are constructed using drilling methods. Wells used for irrigation purposes are generally deep.

4.9.1. Digging

Wells in shallow and unconsolidated glacial and alluvial aquifers can be dug by hand using a pick and shovel. Loose material is brought to the surface in a container by means of rope and pulleys. The depth of a dug well may vary from about 3 to 15 m depending upon the position of the water table. Dug wells usually have large diameter ranging from about 1 to 5 m. Dug wells must penetrate about 4 to 6 m below the water table. The yield of the dug wells is generally small and is of the order of about 500 litres per minute.

4.9.2. Boring

Hand-operated or power-driven earth augers are used for boring a well in shallow and unconsolidated aquifers. A simple auger has a cutting edge at the bottom of a cylindrical container (or bucket). The auger bores into the ground with rotary motion. When the container is full of excavated material, it is raised and emptied. Hand-bored wells can be up to about 20 cm in diameter and about 15 m deep. Power-driven augers can bore holes up to about 1 m in diameter and 30 m deep (4).

4.9.3. Driving

In this method, a series of connected lengths of pipe are driven by repeated impacts into the ground to below the water table. Water enters the well through a screened cylindrical section which is protected during driving by a steel cone at the bottom. Driven wells can be installed only in an unconsolidated formation relatively free of cobbles or boulders. The diameters of driven wells are in the range of about 3–10 cm. Such wells can be constructed up to about 10 m, if hand driven, and up to about 15 m when heavy hammers of about 300 kg are used. The maximum yield of driven wells is usually around 200 litres per minute. The main advantage of a driven well is that it can be constructed in a short time, at minimum cost, and by one man.

4.9.4. Jetting

The jetting (or jet drilling) method uses a chisel-shaped bit attached to the lower end of a pipe string. Holes on each side of the bit serve as nozzles. Water jets through these nozzles keep the bit clean and help loosen the material being drilled. The fluid circulation system is similar to that of a direct rotary drilling method. With water circulation maintained, the drill rods and the bit are lifted and dropped in manner similar to cable tool drilling but with shorter strokes. Jet drilling is limited to drilling of about 10 cm diameter wells to depths of about 60 m, although larger diameter wells have been drilled up to about 300 m by this method (6). Other drilling methods have replaced jet drilling for deep and larger diameter wells.

4.9.5. Cable Tool Drilling

It is the earliest drilling method developed by the Chinese some 4000 years ago. A cable tool drilling equipment mainly consists of a drill bit, drill stem, drilling jars, swivel socket, and cable (Fig. 4.10). The cable tool drill bit is very heavy (about 1500 kg) and crushes all types of earth materials. The drill stem provides additional weight to the bit and its length helps in maintaining a straight vertical hole while drilling in hard rock. The length of the drill stem varies from about 2 to 10 m and its diameter from 5 to 15 cm. Its weight ranges from 50 to 1500 kg. Drilling jars consist of a pair of linked steel bars and help in loosening the tools when these stick in the hole. Under the normal tension of the drilling line, the jars are fully extended. When tools get stuck, the drilling line is slackened and then lifted upward. This causes an upward blow to the tools which are consequently released. The swivel socket (or rope socket) connects the string of tools to the cable. The wire cable (about 25 mm in diameter) which carries and rotates the drilling tool on each upstroke is called the drill line. The cable tool drilling rig mainly consists of a mast, a multiline hoist, a walking beam, and an engine. Drill cuttings are removed from the well by means of bailers having capacities of about 10 to 350 litres. A bailer is simply a pipe with a valve at the bottom and a ring at the top for attachment to the bailer line. The valve allows the cuttings to enter the bailer but prevents them from escaping. Another type of bailer is called the sand pump or suction bailer which is fitted with a plunger. An upward pull on the plunger produces a vacuum which opens the valve and sucks sand or slurried cuttings into the tubing. Most sand pumps are about 3 m long.

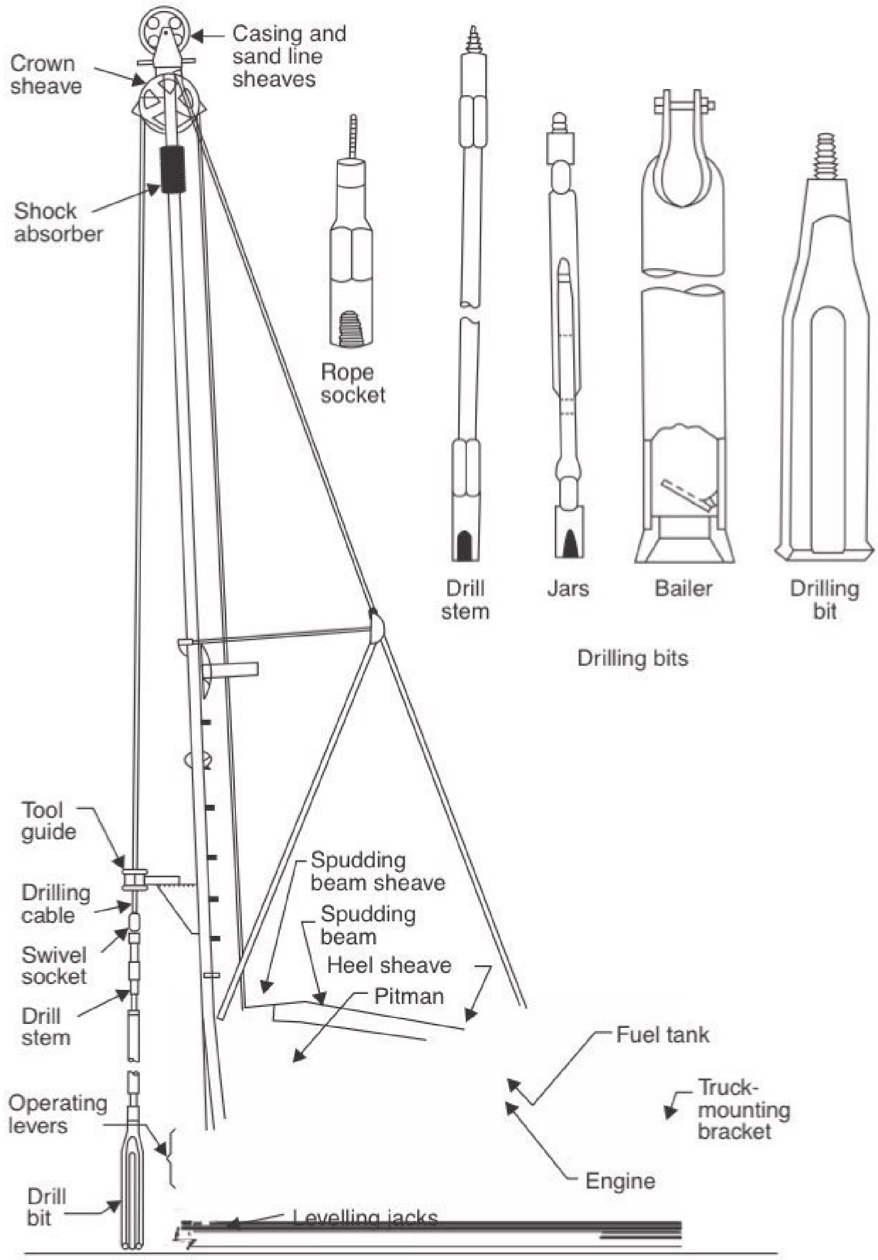

Fig. 4.10 Line sketch of a typical cable tool drilling rig (6)

While drilling through consolidated formations, most boreholes are drilled as "open hole", *i.e.,* no casing is used during the drilling operation. In such conditions the cable tool bit is essentially a crusher. On the other hand, there is a danger of caving in while drilling through unconsolidated formations. For this reason, the casing pipe must follow the drill bit closely to keep the borehole open in unconsolidated formations. Also, in the case of such formations, the drilling action of the bit is primarily a loosening and mixing process. Actual crushing would take place only if a large stone or boulder were encountered.

For the driving operation of the casing pipe, a drive head is fitted to the top of the casing. The drive head serves as an anvil and protects the top of the casing. Similarly, a drive shoe made of hardened and tempered steel is attached to the lower end of the casing pipe. The shoe prevents the damage to the bottom end of the casing pipe when it is being driven. The casing is driven down by means of drive clamps, constructed of heavy steel forgings made in halves, fastened to the top of the drill stem. Drive clamps act as the hammer face and the up-and-down motion of tools provides the weight for striking the top of the casing pipe and thus driving it into the ground.

The procedure for drilling through unconsolidated formation consists of repeated driving, drilling, and bailing operations. The casing pipe is initially driven for about 1 to 3 m in the ground. The material within the casing pipe is then mixed with water by the drill bit to form slurry. The slurry is bailed out and the casing pipe is driven again. Sometimes, the hole is drilled 1 to 2 m below the casing pipe; the casing is then driven down to the undisturbed material and drilling is resumed. The drilling tools make 40 to 60 strokes of about 40 to 100 cm length every minute. The drill line is rotated during drilling so that the resulting borehole is round. The slurry formed by the mixing of cuttings with added water (if not encountered in the ground) reduces the friction on the cutting bit and helps in bailing operations.

If the friction on the outside of the casing pipe increases so much that it cannot be driven any more or if further driving might damage the pipe, a string of smaller casing is inserted inside the first one. Drilling is thus continued. Sometimes, two or three such reductions may be required to reach the desired aquifer. The diameter of the well is reduced. If such a situation is anticipated, the casing in the upper part should be of larger diameter. The drilling process through consolidated formation, not requiring casing, would consist of repeated drilling and bailing operations only.

The cable tool method has survived for thousands of years mainly because of its suitability in a wide variety of geological conditions. It offers the following advantages (6):

(*i*) Cable tool drilling rigs are relatively cheaper.

(*ii*) The rigs are simpler and do not require sophisticated maintenance.

(*iii*) The machines have low power requirements.

(*iv*) The borehole is stable during the entire drilling operation.

(*v*) Recovery of reliable samples is possible at every depth.

(*vi*) Wells can be drilled in water-scarce areas.

(*vii*) Because of their size, the machines can be operated in more rugged, inaccessible terrain or in other areas where limited space is available.

(*viii*) Wells can be drilled in formations where water is likely to be lost.

Slow driling rate, higher cost of casing pipe, and difficulty in pulling back long strings of casing pipes are some of the disadvantages of cable tool drilling.

4.9.6. Direct Rotary Drilling

Direct rotary drilling is the fastest method of drilling deep wells of diameters of up to 45 cm (or more with the use of reamers) through unconsolidated formations. The drilling bit is attached to a heavy drill pipe which is screwed to the end of the kelly which is a drill pipe of square section (Fig. 4.11). The drill collar or stabilizer helps in maintaining, straight hole in soft formations through its large wall contact. The drill pipe is turned by a rotating table which fits closely round the kelly and allows the drill rod to slide downward as the hole deepens. The drilling rig consists of a mast, a rotating table, a pump, a hoist, and an engine. The borehole is drilled by rotating a hollow bit attached to the lower end of a string of a drill pipe. Cuttings are

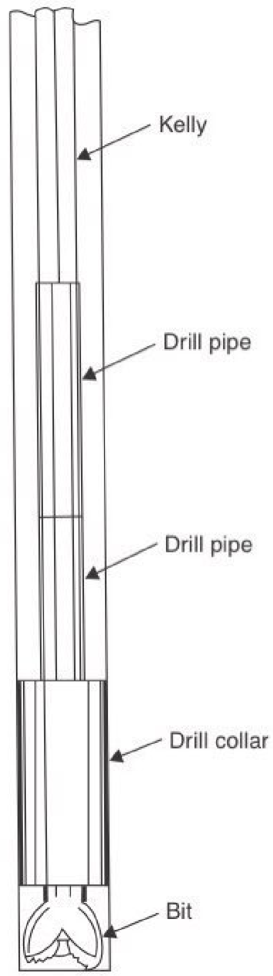

Fig. 4.11 Drill string for rotary drilling

removed continuously by pumping drilling fluid (a mixture of clay and water with some additives to make it viscous) down the drill pipe and through the orifices in the bit. The drilling fluid then flows upward through the annular space between the drill pipe and the borehole, carrying the cuttings in suspension to the surface settling pits where the cuttings settle down in the pits. The clear drilling fluid is pumped back into the borehole. The settling pits can either be portable or excavated for temporary use during drilling and then backfilled after completion of the well. Usually no casing is required during drilling because the drilling mud forms a clay lining on the borehole walls which prevents the formation materials from caving in. After drilling, the casing pipe with perforated sections opposite the aquifers is lowered into the borehole. The drilling rotary method has become the most common due to its following advantages (6):

(*i*) Drilling rates are relatively high.

(*ii*) Minimum casing is required during drilling.

(*iii*) Rig mobilisation and demobilisation are fast.

(*iv*) Well screens can be set easily as part of the casing installation.

Some of the major disadvantages of the direct rotary method are as follows (6):

(*i*) Drilling rigs are expensive.

(*ii*) It is costly to maintain them.

(*iii*) The mobility of the rigs is restricted depending on the slope and wetness of the land surface.

(*iv*) The collection of accurate samples requires special procedure.

(*v*) The drilling fluid may cause the plugging of some aquifer formations.

4.9.7. Reverse Rotary Drilling

The direct rotary drilling method is capable of drilling boreholes with a maximum diameter of about 60 cm. High-capacity wells, particularly those with filter pack, need to be much larger in size. Besides, the drilling rate becomes smaller with increase in borehole diameter in the case of direct rotary drilling. To overcome these limitations, the reverse rotary drilling technique has been developed. This technique is capable of drilling boreholes of about 1.2 m diameter in unconsolidated formation. Recently, the reverse rotary method has been used in soft consolidated rocks such as sandstone, and even in hard rocks using both water and air as the drilling fluid (6).

In reverse rotary drilling, the flow of the drilling fluid is opposite to that in direct rotary drilling. The reverse rotary drilling rig is similar to the direct rotary drilling rig except that it requires larger-capacity centrifugal pumps, a larger diameter drill pipe, and other components also of larger size. The drilling fluid moves down the annular space between the borehole wall and the drill pipe, and picks up the cuttings before entering the drill pipe through the ports of the drill bit. The drilling fluid, along with its cuttings load, moves upwards inside the drill pipe which has been connected to the suction end of the centrifugal pump through the kelly and swivel. The mixture is brought to a settling pit where the cuttings settle at the bottom and the drilling fluid (*i.e.,* muddy water) moves down the borehole again. The drilling fluid is usually water mixed only with fine-grained soil. The hydrostatic pressure and the velocity head of the drilling fluid moving down the borehole supports the borehole wall. To prevent the formation from caving in, the fluid level must always be up to the ground surface even when drilling is suspended temporarily. The advantages of the reverse rotary drilling method are as follows (6):

(*i*) The formation near the borehole is relatively undisturbed compared to other methods.

(*ii*) Large-diameter holes can be drilled rapidly and economically.

(*iii*) No casing is required during the drilling operation.

(*iv*) Well screens can be set easily while installing the casing.

(*v*) The boreholes can be drilled through most geologic formations, except igneous and metamorphic rocks.

(*vi*) Because of the low velocity of the drilling fluid, there is a little possibility of its entering the formation.

The disadvantages of the reverse rotary drilling method are as follows (6):

(*i*) A large quantity of water is needed.

(*ii*) The reverse rotary drilling rig is costlier because of larger size of equipment.

(*iii*) Large mud pits are required.

(*iv*) Some drill sites may be inaccessible because of the larger size of the rig.

4.10. WELL COMPLETION

After drilling a well, the well screen and filter pack (wherever necessary) are to be placed and the casing removed. If the formations are sufficiently strong and stable, ground water may directly enter the uncased well. In unconsolidated formations, however, a casing with perforation (or a well screen) is needed to support the outside material and also to admit water freely into the well.

The installation of the well screen and the removal of the casing is best done by the pull-back method in which the casing is installed to the full depth of the well and the well screen, whose size is smaller than that of casing, is lowered inside the casing. The casing is then pulled back or lifted far enough to expose the screen to the water-bearing formation (Fig. 4.12).

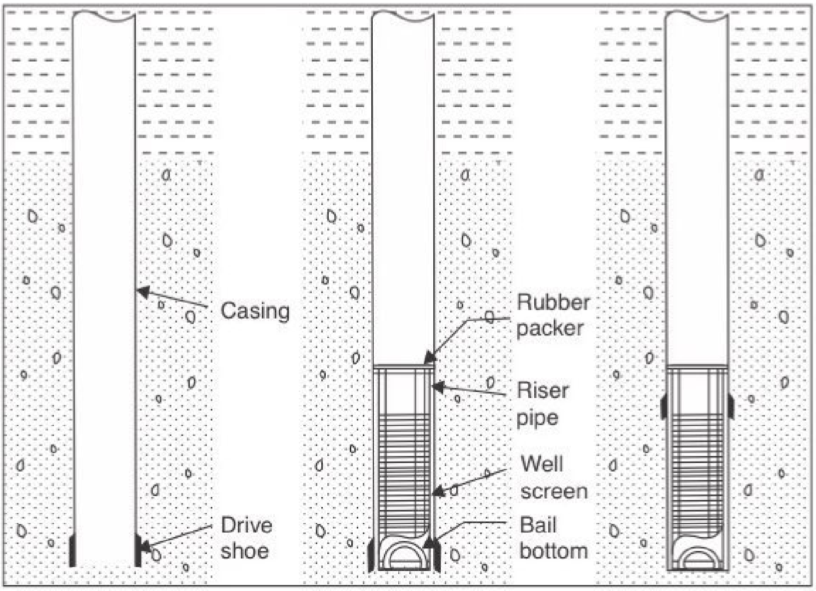

Fig. 4.12 Pull-back method of installing screen

In the case of rotary-drilled wells, setting the casing to the bottom of the hole and then pulling it back may appear to be extra and unnecessary work in view of the drilling fluid supporting the borehole wall. But this extra work prevents serious problems which may arise on account of premature caving in which may occur when the viscosity of the drilling fluid is reduced prior to development. This casing is also useful when there is likely to be a longer period between drilling and screen installation, and during which period a momentary loss of drilling fluid may cause partial collapse of the borehole.

A filter pack is generally placed in large-diameter wells by the reverse circulation of the fluid in the well as the filter pack material is fed into the annular space outside the screen by a continuous-feed hopper. When the filter pack material fills the space around the well screen, the transporting water is drawn upward through the screen openings (Fig. 4.13).

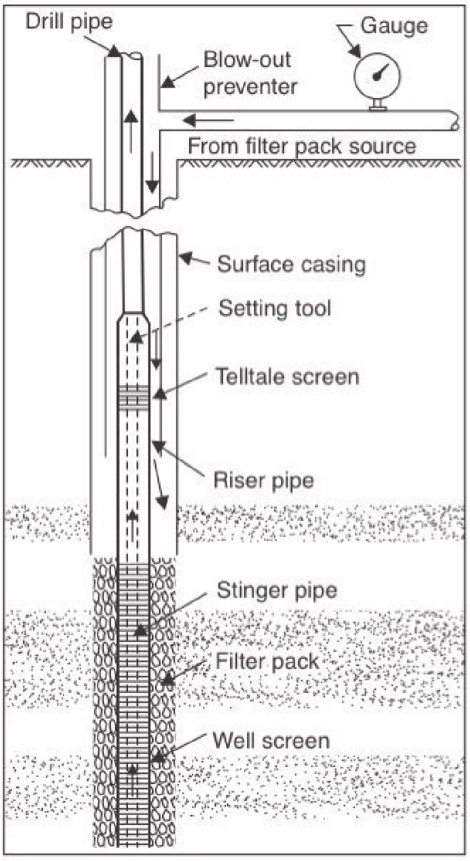

Fig. 4.13 Filter packing of wells

4.11. DEVELOPMENT OF WELLS

Drilling operations for well excavation change the hydraulic characteristics of the formation materials in the vicinity of the borehole. Very often, these changes result in the reduction of the hydraulic conductivity close to the borehole. When a well is drilled with a cable tool rig equipped with a casing driver, the repeated blows on the casing rearrange the grains in the vicinity of the casing. In rotary drilling methods, the drilling fluids containing clay may flow into the aquifer for some distance and thus plug the pore spaces of the permeable formation. Before commissioning the well for use, it is, therefore, necessary to repair the damage done to the aquifer by the drilling operations. Besides, there is also a need to improve the basic physical characteristics of the aquifer in the vicinity of the well screen so that water can flow more freely into the well. A well is, therefore, 'developed' in order to attain these two objectives, and thus, maximise well yield. Well development involves applying some form of energy to the water-bearing formation in the vicinity of the well so as to remove fine materials (including drilling mud) from the aquifer and rearrange formation particles so that the well yields clear sand-free water in maximum quantity with minimum drawdown. Well development serves the following beneficial purposes :

(*i*) It increases the permeability of the aquifer material surrounding the well and filter pack (if present) by:

(*a*) reducing the compaction and intermixing of grains of different sizes during drilling by removing fine grains,

(*b*) removing the filter cake or drilling fluid film that coats the borehole,

(*c*) removing much or all of the drilling fluid which has entered the aquifer,

(*d*) breaking sand-grain bridging across the screen openings, and

(*e*) increasing the natural porosity of the previously undisturbed formation near the borehole by removing the finer fraction of the aquifer material.

(*ii*) It creates a graded zone of aquifer material around the screen in a naturally developed well. This effect stabilises the formation so that the well will yield sand-free water.

(*iii*) It reduces the head loss near the well screen.

(*iv*) It increases the useful life of the well screen.

(*v*) It brings the well to its maximum specific capacity, *i.e.,* the maximum yield at minimum drawdown.

The methods usually adopted for well development are as follows (6):

(*i*) Overpumping,

(*ii*) Backwashing.

(*iii*) Mechanical surging,

(*iv*) Air surging and pumping,

(*v*) High-velocity jetting, and

(*vi*) High-velocity water jetting combined with simultaneous pumping.

There are several variations of most of these methods (16). Only the main features of these methods have been described in the following paragraphs.

4.11.1. Overpumping

In the ovrpumping method, the well is pumped at a discharge rate higher than the discharge rate of the well during its normal operation. The logic of the method is that any well which can be pumped sand-free at a high rate can be pumped sand-free at a lower rate. It is the simplest method of developing wells. However, the development by this method is not effective and the developed well is seldom efficient. The aquifer material is also not fully stabilised. This incomplete development is due to the following reasons:

(*i*) Water flows in only one direction and some sand grains may be left in a bridged condition. The formation is thus partially stabilised.

(*ii*) Most of the development takes place in the most permeable zones of the aquifer which are usually closest to the top of the screen. Therefore, less development takes place in the lower layers of the aquifer.

Besides, this method generally uses the pump intended for regular use during the normal operation of the well. Pumping of silt-laden water at higher rates can reduce efficiency of the pump.

4.11.2. Backwashing

Reversal of flow through the screen openings agitates the aquifer material, removes the finer fraction and rearranges the remaining aquifer particles. These effects usually cause effective development of the well. The "rawhiding" method of backwashing consists of alternately lifting a column of water significantly above the pumping level and then letting the water fall back into the well. To minimise the changes of sand-locking the pump, its discharging rate should be gradually increased to the maximum capacity before stopping the pump. During this process, the well is occasionally pumped to waste to remove the sand brought to the well by the surging action of this method of well development. As in the case of the overpumping method, the surging action may be concentrated only in the upper layers of the aquifer. Besides, the surging effect is not vigorous enough to cause maximum benefits. When compared with other methods of well development, the overall effectiveness of backwashing as well as overpumping methods in case of high-capacity wells is rather limited.

4.11.3. Mechanical Surging

In this method, a close-fitting surge plunger, moving up and down in the well casing, forces water to flow into and out of the well screen. The initial movements of the plunger should be relatively gentle so that the material blocking the screen may go into suspension and then move into the well. To minimise the problem of the fine materials going back to the aquifer from the well, the fine material should be removed from the well as often as possible. The surging method is capable of breaking sand bridges and produces good results. However, it is not very effective in developing filter-packed wells because the water movement is confined only up to the filter pack and the aquifer remains unaffected by the surging action.

4.11.4. Air Surging and Pumping

This method requires two concentric pipes – the inner pipe known as the air line and the outer one known as the pumping pipe (or eductor pipe). The assembly of these pipes is lowered into the well. In air surging, compressed air is injected through air line into the well to force aerated water up through the annular space between the air line and the pumping pipe. As this aerated water reaches the top of the casing, the air supply is stopped so that aerated water column starts falling. Air-lift pump is used to pump the well periodically to remove the sand brought into the well as a result of air surging. The compressed air produces powerful surging action. This method is used to develop wells in consolidated and unconsolidated formations.

4.11.5. High-Velocity Jetting

This method consists of shooting out high-velocity jets of water from a jetting tool to the aquifer through the screen openings. The equipment of this method consists of a jetting tool provided with two or more equally spaced nozzles, high-pressure pump, high-pressure hose and connections, and a water supply source. The forceful action of high-velocity jets loosens the drilling mud and agitates, and rearranges the sand and gravel paritcles around the well. The loosened material is removed by pumping. In this method of development, the entire surface of the screen can be subjected to vigorous jet action by slowly rotating and gradually raising and lowering jetting tool.

This method has the following advantages:

(*i*) The energy is concentrated over a small area with greater effectiveness.

(*ii*) Every part of the screen can be developed selectively.

(*iii*) The method is relatively simple.

The method of jetting is particularly successful in developing highly stratified and unconsolidated water-bearing formations.

4.11.6. High-Velocity Water Jetting Combined with Simultaneous Pumping

The method of high-velocity water jetting results in very effective development of wells. But, maximum development efficiency can be obtained by combining high-velocity water jetting with simultaneous air-lift pumping method (Fig. 4.14). The method requires that the volume of water pumped from a well will always be more than that pumped into it so that the water level in the well is always below the static level and there is a continuous movement of water from the aquifer to the well. This would help remove some of the suspended material loosened by the jetting operation (6).

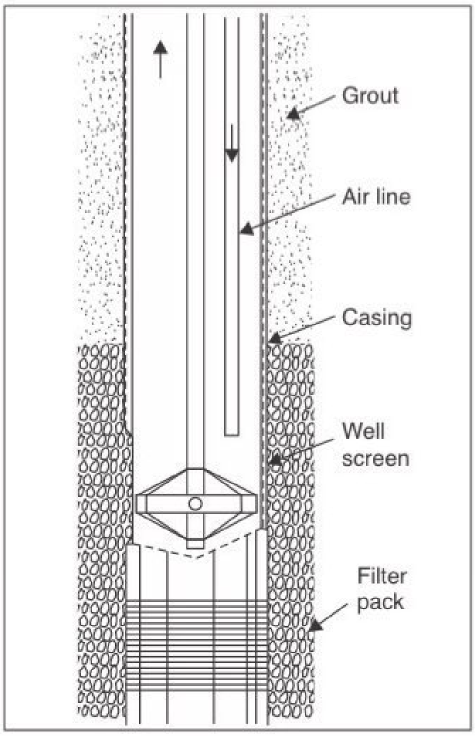

Fig. 4.14 Jetting and air-lift pumping

4.12. PUMPING EQUIPMENT FOR WATER WELLS

In most wells, the static water level is below the ground surface and, hence, flowing wells are rare. The water has to be lifted from inside the well to the ground surface. Rope and bucket with or without windlass have been used and are still used for shallow wells and for low discharges. For deeper wells and high yields of water, pumps have to be used.

The purpose of installing pumps in wells is to lift water from inside the well to the ground surface. Pumps can be broadly classified as shallow well pumps and deep well pumps depending upon the position of the pump and not the depth of the well. A shallow well pump is installed on the ground and lifts water from the well by suction lift. A deep well pump is installed within the well casing and its inlet is submerged below the pumping level. If the pumping level is lower than the limit of a suction lift (about 7.5 m), only the deep well pump should be used.

Pumps are also classified on the basis of their design as positive displacement pumps and variable displacement pumps (6). Positive displacement pumps discharge almost the same volume of water irrespective of the head against which they operate. The input power, however, varies in direct proportion to the head. Such pumps are used extensively in ground water monitoring wells, hand pump-equipped wells, and wind-powered wells. They are rarely used for large-capacity water wells. The most common type of positive displacement pumps is the piston pump.

The variable displacement pumps are used for large-capacity wells. For these pumps, there is an inverse relationship between the discharge and the working head. Maximum input power is required when the pump has to operate at low heads delivering large volumes of water. The major types of variable displacement pumps are as follows (6):

(*i*) Centrifugal pumps:
   (*a*) suction lift pump,
   (*b*) deep-well turbine pump, and
   (*c*) submersible turbine pump.

(*ii*) Jet pumps

(*iii*) Air-lift pumps

4.12.1. Centrifugal Pumps

Centrifugal pumps are the most popular. They are capable of delivering large volumes of water against high as well as low head with good efficiency. Besides, these pumps are relatively simple and compact. The basic principle of centrifugal pumping can be understood by considering the effect of swinging a bucket of water around in a circle at the end of a rope. The centrifugal force causes the water to press against the bottom of the bucket rather than spill out of the bucket. If a hole is cut in the bottom, water would discharge through the opening at a velocity which would depend on the centrifugal force. If an airtight cover were put on the bucket top, a partial vacuum would be created inside the bucket as the water would leave through the opening in the bottom. If a water source is connected to the airtight cover through an intake pipe, the partial vacuum will draw additional water into the bucket as the water is being discharged through the bottom hole. The bucket and cover of this example correspond to the casing of a centrifugal pump; the discharge hole and the intake pipe correspond to the pump outlet and inlet, respectively; the arm that swings the bucket corresponds to the energy source and the rope performs the function of a pump impeller.

Suction-lift pumps create negative pressure at the pump intake. The atmospheric pressure at the free surface of water in the well forces the well water into and up the intake pipe. The maximum suction lift depends on the atmospheric pressure (10.4 m of water head), vapour pressure of water, head loss due to friction, and the head requirements of the pump itself. Under field conditions, the average suction-lift capability of a suction-lift centrifugal pump is about 7.5 m (6).

A deep-well vertical turbine pump consists of one or more impellers housed in a single- or multi-stage unit called a bowl assembly. Each stage gives a certain amount of lift and sufficient number of stages (or bowl assemblies) are assembled to meet the total head requirement of the system (6).

Vertical turbine pumps in high-capacity wells are highly reliable over long periods of time. The motors of these pumps are not susceptible to failure caused by fluctuations in electric supply. Motor repairs can be carried out easily because of their installation on the ground surface. These pumps, however, cannot be used in wells which are out of the alignment. Besides, these pumps require highly skilled personnel for installation and service.

Submersible pumps have bowl assemblies which are the same as those of vertical turbine pumps. But, the motor of the submersible pump is submerged and is directly connected to and located just beneath the bowl assembly. Water enters through an intake screen between the motor (at lower level) and the bowl assembly (at higher level), passes through various stages, and is discharged directly through the pump column to the surface (6).

The motor of a submersible pump is directly coupled to impellers and is easily cooled because of complete submergence. Ground surface noise is also eliminated. The pump can be mounted in casings which are not entirely straight. The pump house is also not necessary. There are, however, electrical problems associated with submerged cables. These pumps cannot tolerate sand pumping and work less efficiently. The motor is less accessible for repairs and cannot tolerate voltage fluctuations.

4.12.2. Jet Pumps

The jet pump is a combination of a centrifugal pump and a nozzle-venturi arrangement as shown in Fig. 4.15. The nozzle causes increased velocity and reduced pressure at point A. The lowered pressure at A draws additional water from the intake pipe and this water is added to the total volume of water flowing beyond A. The venturi tube helps in the recovery of pressure at B with minimum loss of head. Compared to centrifugal pumps, jet pumps are inefficient but have some advantageous features too. These are adaptable to small wells down to a 5 cm inside diameter. All moving parts of the jet pump are accessible at the ground surface. Their design is simple and results in low equipment and maintenance costs.

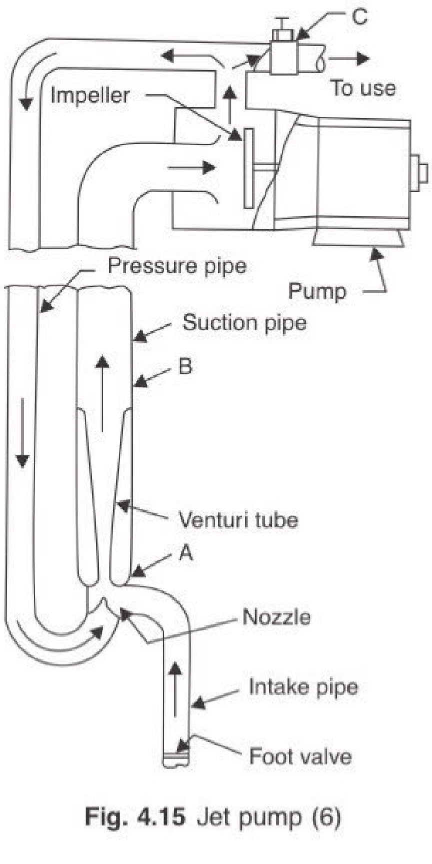

Fig. 4.15 Jet pump (6)

4.12.3. Air-Lift Pumps

Water can also be lifted inside a well by releasing compressed air into an air discharge pipe (air line) lowered into the well. Because of the reduced specific gravity, aerated water is lifted to the ground surface. Air-lift pumping is inefficient and requires cumbersome and expensive equipment and is, therefore, rarely used as a permanent pumping system.

The main factors which must be considered while selecting a pump for water well are the anticipated pumping conditions, specific installation and maintenance conditions, and the basic pump characteristics. As in well construction, the initial cost of a pump and its installation are relatively less important than the performance, reliability, and operating costs during the life span of the pumping equipment.

EXERCISES

4.1 In what respects is ground water better than surface water? Compare well irrigation with canal irrigation.

4.2 What is the meaning of conjunctive use? Why is it useful to consider it in water resources planning?

4.3 Compare surface and subsurface methods of ground water exploration.

4.4 Discuss in brief the steps for designing various components of a water well.

4.5 Describe different methods of well drilling, mentioning their merits and suitability for different field conditions.

4.6 What are the benefits of well development? Describe various methods of well development.

4.7 A constant head permeability test was carried out on a soil sample of diameter 10 cm and length 15 cm. If 100 cc of water was collected in 100 s under a constant head of 50 cm, determine the coefficient of permeability of the soil sample.

4.8 Calculate the amount of water flowing into a coastal aquifer extending to a length of 30 km along the coast for the following data:

Average permeability of the aquifer	= 40 m/day
Average thickness of the aquifer	= 15 m
Piezometric gradient	= 5 m/km

4.9 A 20 cm well completely penetrates an artesian aquifer. The length of the strainer is 16 m. What is the well yield for a drawdown of 3 m when the coefficient of permeability and the radius of influence are 30 m/day and 300 m, respectively.

4.10 A well with a radius of 0.5 m completely penetrates an unconfined aquifer with $K = 32$ m/day and the height of water table above the bottom of the aquifer being 45 m. The well is pumped so that the water level in the well remains 35 m above the bottom of the well. Assuming that pumping has essentially no effect on the water table at a distance of 300 m from the well, determine the steady-state well discharge.

4.11 A fully penetrating artesian well is pumped at a rate of 1500 m^3/day from an aquifer whose S and T values are 4×10^{-4} and 0.145 m^2/min, respectively. Find the drawdowns at a distance 3 m from the production well after one hour of pumping, and at a distance of 350 m after one day of pumping.

4.12 The values of drawdowns were observed in an observation well located at a distance of 3 m from a fully penetrating artesian well pumping at 2.2 litres per second. The drawdowns were 0.75 and 0.95 m after two and four hours of pumping respectively. Determine the aquifer constants S and T.

4.13 Two tubewells of 200 mm diameter are spaced at 120 m distance and penetrate fully a confined aquifer of 12 m thickness. What will be the percentage decrease in the discharge of each of these wells as a result of pumping both wells simultaneously with a depression head (*i.e.* drawdown) of 3 m in either case. Assume permeability of the aquifer as 40 m/day and the radius of influence as 200 m.

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